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RESEARCH AND DEVELOPMENT OF AN AIRBORNE HYGROSCOPIC SPRAY SYSTEM

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RESEARCH AND DEVELOPMENT OF AN AIRBORNE HYGROSCOPIC SPRAY SYSTEM

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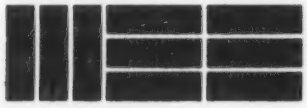

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16. ABSTRACT

Three different atomization techniques: direct pressure nozzles, air jet nozzles and spinning cylinder devices, were investigated to determine which would be most suitable for development into an airborne hygroscopic spray system. The system was to be capable of producing controlled droplet spectrums ranging from 20μm MMD to 200μm MMD, of an ammonium nitrate-urea solution to be used as a hygroscopic seeding material. The system was to be capable of atomizing the solution at rates of 2 liters per second. Tests were conducted under static no wind conditions and in a 110 m/s air stream. The atomization device that proved most suitable was a direct pressure impaction type nozzle. A prototype airborne spray system has been designed using this type of nozzle.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- Air Nozzles, Airborne Spray System, Atomization, Cloud Seeding, Direct Pressure Nozzles, Drop Size Distribution, Hygroscopic Spray System, Nozzles, Spinning Cylinder Atomizers, Spray System

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SUMMARY

Project goals were to devise a system that would produce aerosols of ammonium nitrate-urea solution in the following drop size categories:

(1) 20-30μm MMD

(2) 50-100μm MMD

(3) 100-200μm MMD

An investigation of several atomization techniques was undertaken to determine which would be most suitable for development into an airborne system for producing a controllable droplet spectrum of the hygroscopic seeding material. Of the techniques found capable of producing droplets in the desired size categories, only one, the use of direct pressure impaction type nozzles, was found to be practical within the limitations imposed. The limitations were those imposed by the desire to be able to operate the atomization system from an aircraft with approximately the load carrying capability of a DC-3. Thus there were practical restrictions as to the size, weight, reliability, and especially the power requirements of the system.

It was desired that the drop size spectrum be narrow enough so that 90% of the mass of particles be contained in a range defined as follows: no more than 5% of the mass of the particles should be in a size range smaller than 0.5 x MMD and no more than 5% should be larger than 1.8 x MMD. None of the devices tested proved capable of meeting this narrowness criterion under all operating conditions. As shown by Fig. 11, the direct pressure impaction type nozzles proved capable of producing approximately 80% of the particles in the desired spectral range. For nozzles producing droplets with MMD's 50μm and larger there were no particles larger than 1.8 x MMD and approximately 12% were smaller than 0.5 x MMD. For nozzles producing droplets smaller than 50μm MMD approximately 10% of the particles were larger than 1.8 x MMD and 10% were smaller than 0.5 x MMD.

The seeding material is a water solution of ammonium nitrate and urea. A typical solution contains a mixture of approximately 44% (by weight) of ammonium nitrate, 36% urea, and 20% water. All atomization tests during this project were conducted either with a solution containing the above proportions or with fresh water. The density of the solution used was 1.32 g/cm^3, viscosity at room temperature (22°C) approximately 5 centipoise, and surface tension approximately 50 dynes per centimeter. Commercial grade (Union 76 Collier's) ammonium nitrate and urea fertilizers were used for all tests.

The airborne system is to be capable of producing aerosols in the above size categories at rates of up to 2 liters per second, and is to be capable of dispersing into a 50 to 100 meter per second airstream without significantly affecting the drop size distribution.

From the beginning several fundamental problems were recognized. One had to do with reliably producing droplets in the 20-30μm size category with reasonable efficiency so that excess power would not be required. The fertilizer solution proved to be highly corrosive to many materials, and the large amount of dissolved solids contained offered the possibility that "salting out" could be a problem. Clogging and fouling of the atomization device could obviously affect reliability and maintenance. The large flow rates required made power consumption an important factor.

The investigation showed that the power required to produce 2 liters/second of 20μm MMD aerosol may vary from less than 25 HP for direct pressure nozzles to over 600 HP for air jet nozzles. Another anticipated problem had to do with the possibility that droplets in the larger size categories might be broken up by the blast of the airstream. This proved to be a significant problem but one that could be overcome simply by shielding the nozzles from the direct blast of the airstream.

At the start of the project the most serious problem was that of reliably producing droplets in the smallest size category without the need for excessive power and without undue clogging of the atomizing device. Another problem was dispersing the aerosol into a high velocity airstream and determining and controlling the drop size distribution in that airstream. Finally an airborne prototype of an atomization system had to be designed.

The project was divided into three stages. The basic task of Stage I was to find a device capable of producing aerosols of ammonium nitrate-urea-water solution with a 20 to 30μm MMD. All tests in Stage I were conducted under static conditions (zero wind velocity) in an aerosol test chamber. During Stage I it was determined that both direct pressure nozzles and air jet nozzles would be capable of producing 20 to 30μm MMD solution droplets but that air nozzles would require up to approximately 25 times more power. One commercially available spinning cylinder device (the Beecomist Model 350) was tested and found to produce droplets larger than 200μm MMD.

The direct pressure impaction type nozzles tested proved quite capable of atomizing the test solution into 20μm MMD or smaller particles. The solution flowed quite easily through the nozzles and did not show any tendency to salt out or to in any way clog the nozzle orifice as long as reasonable precautions were taken to filter out undissolved solids.

Initial tests were also conducted to determine the chemical compatibility of various materials used in the atomization system with the ammonium nitrate-urea solution. The chemical compatibility test demonstrated dramatically that brass and copper were not suitable materials but that stainless steel, aluminum and various plastics were suitable.

Stage II was assigned the task of determining the optimum feasible design for an in-flight atomization system and most tests were conducted in a high velocity airstream. Further tests were conducted with both air jet nozzles and spinning devices, but the bulk of the effort was concentrated on direct pressure nozzles. Direct pressure nozzles proved to be the simplest and therefore the most reliable devices, and by far the most efficient in terms of power requirements.

Tests were conducted under conditions simulating flight speeds of 110 meters per second (250 mph); and under static, no-wind conditions. All of the devices tested were capable of producing droplets in the desired size categories but the direct pressure nozzles proved to be the most practical solution.

Tests showed that using air nozzles (a two fluid device using compressed air jets to atomize the liquid) to produce 20μm MMD solution droplets at a rate of 2 liters per second would require 300-600 HP. Spinning devices could accomplish this output with a power consumption of only about 50 HP but would require 120 spinning cylinders each rotating at approximately 70 000 rpm (an impractical solution). Direct pressure nozzles require less than 25 HP to produce the same results.

In the airstream nozzles were tested at different orientations to the air blast, but with the spinning cylinders the air blast was always parallel to the spinning axis of the cylinder. With the nozzles it was found that the drop size distribution varied considerably depending upon the orientation of the nozzles, and that the best orientation was with the nozzle orifice being protected from the direct blast of the air stream. If the nozzles were facing directly into the air blast, totally unpredictable results were obtained. If the nozzles were oriented so that the fluid jets were 90° to the airstream, the results were still unsatisfactory, but the disrupting effect of the airstream could be almost totally overcome by orienting the nozzles so that they faced downstream and thus protecting the orifices from a direct air blast. This proved to be desirable because it allowed for much better control of the drop size distribution.

The effort in Stage III was directed toward design of an airborne prototype system using direct pressure impaction type

nozzles. A system was designed with the capability of varying output rates from about 0.6 liter per second to 2.8 liter per second, and of producing controllable MMD's varying from 20μm to 250μm. Power requirements for the system are less than 25 HP. Design details are given in the text of this report.

NOTE ON UNITS USED:

Throughout this report mathematical values and dimensions are given in both metric and English units. The units used are those most commonly used in machinery in the U.S. and in Europe. Wherever possible the metric International System of Units (SI) has been adhered to. However, for practical reasons there are some exceptions to this. For example, power output of motors and engines is given in horsepower instead of watts or kilowatts. The only accepted SI unit of pressure is now the pascal. However, for practical reasons pressures are given in units most commonly found on pressure gauges and most commonly used in pump specifications. The units used are the pound per square inch (psi) and the kilogram per square centimeter (kg/cm^2), even though it is realized that neither the pound nor the kilogram is an accepted unit of force. However, there should be no confusion if it is kept in mind that when pounds or kilograms are used to define the force involved in pressure, what is really meant is the force that would be required to suspend a 1 pound mass or a 1 kilogram mass in the earth's gravitational field. Thus these forces would be units of MLT^{-2}.

STAGE I

STATIC TESTS IN AN AEROSOL TEST CHAMBER

1. The Chamber

Atomization tests were conducted in a 12 m^3 aerosol test chamber measuring approximately 2 meters x 2.5 meters x 2.5 meters high. The chamber is equipped with two liquid sources and a source of compressed air capable of delivering 14 liters per second (30 cfm) at 7.7 kg/cm^2 (110 psi). One liquid source is driven by a high pressure pump which can deliver fluids at pressures up to 49 kg/cm^2 (700 psi). The other source is driven by gas pressure from 155 kg/cm^2 (2200 psi) nitrogen tanks and is capable of delivering fluids at pressures of up to 105 kg/cm^2 (1500 psi), the maximum working pressure for the fluid tank. The lab is also equipped to measure accurately liquid flows as low as 0.5 ml/s (.008 gpm) to flows as high as 1.6 l/s (25 gpm).

In a typical test the atomizing device being tested would be run long enough to assure that the room air was saturated. Then a representative sample of the aerosol would be collected on a microscope slide coated with 1000 Centistoke viscosity silicon fluid. The silicon fluid, with a density of approximately 1 g/cm^3, will encapsulate droplets and hold them in suspension long enough for the sample to be photographed with a microscope. Any droplets that do settle out are easily recognizable because of their different optical properties and thus can be easily eliminated when the counting and sizing is done.

All samples are collected by allowing droplets to settle under the influence of gravity onto a slide surface. To assure that a representative sample was obtained, a collecting chamber was used inside of the aerosol test chamber. In sampling 20 to 30μm MMD droplets a cylindrical collecting chamber 30 cm high and approximately 20 cm in diameter was used. This collecting chamber was needed to prevent size biasing in the sample. The sizes of particles in a particular aerosol being tested would typically range from less than 10μm in diameter to almost 100μm in diameter. The fall velocity, as determined by Stokes Law, of a 10μm unit density particle is .03 cm/s. The fall velocity of a 100μm diameter particle is 30 cm/s. Thus if a slide were exposed to the open room for a period of time that was not great enough for all of the small particles in the room to settle out, the sample would be biased toward large particles since proportionately more of them would settle onto the slide. The test chamber is 2.5 meters high and an unreasonably long time would be required to allow all particles to settle out. Experience also showed that too long a sample

time led to too great a sample density on the slide, causing overlapping and coalescence of particles. To eliminate this bias problem the small cylindrical collecting chamber was used. The technique was to let the open ended collecting chamber become full of a representative aerosol sample and then simultaneously close the upper end of the cylinder while exposing a slide at the lower end of the cylinder. Particles of 100μm, if they were present, would precipitate out in one second. Particles of 50μm would precipitate out in approximately 4 seconds. One hundred seconds would be required for all 10μm particles to settle out. Samples were typically taken for a period of 300 seconds so that all particles 6μm and larger would be sampled and then an appropriate correction factor used for those particles less than 5μm. Particles 5μm and smaller typically accounted for less than 1% of the mass of the aerosols so that any error introduced by this approximation would be acceptably small.

Since only a small number of large particles could be collected in any one sample, there was some question as to whether a representative sample of the larger droplets was being obtained. To test this, an impaction sampling technique was used that had poor collection efficiency for small particles but nearly 100% collection efficiency for particles larger than about 25μm. Thus a large and accurate sampling of the larger droplets could be obtained at the expense of obtaining a representative sample for the smaller drops. The two sampling techniques both agreed quite well for the size distribution larger than 25μm so it was concluded that the gravity settling technique was accurate and adequate for the task at hand.

2. Droplet Counting and Sizing

In a typical sampling run 10 samples would be taken and photographed at 75X magnification using 35mm black and white film. Each sample photograph would typically contain 300 or more particles and enough samples were usually taken to obtain total counts of 2000 to as much as 10 000.

It was found that total counts of 1500 to 2000 were quite adequate to give repetitive measurements of MMD with a standard deviation of less than 2μm.

To obtain droplet counts and measurements of the droplet size, images from the developed negative were projected onto a screen at 500X magnification. All droplets from each run were then counted and measured and tabulated into 5μm intervals on a drop size distribution worksheet. The total number of particles counted in each 5μm size category were summarized and these numbers plotted on a drop size distribution graph. The counts in the 0 to 5μm size category were always corrected with an appropriate multiplication factor since it was known that in any given sample all of the small droplets were not collected. A smooth curve was then drawn through the points plotted on the graph. This smoothing was necessary since there was always some scatter in the points for droplets larger than about 50μm because of the small number of particles sampled in these categories. It was realized that this smoothing had to introduce an error since the smooth curve was made strictly according to the judgment and skill of the person doing the counting. However, it was demonstrated that this error was acceptable by making repetitive tests using different forms of judgment in the smoothing and by comparing MMD's determined from samples with more than 10 000 counts where the smoothing error was appropriately less. The standard deviation of MMD's from all methods of smoothing was found to be less than 2μm.

Points from the smoothed curve were then transferred to a mass distribution worksheet and the numbers used to compute the mass in each 5μm size category and thus determine the mass median diameter. This information was then plotted on a mass distribution graph showing both cumulative mass and mass per size category.

3. Tests of Direct Pressure Impaction-Type Nozzles

It was already known that either direct pressure nozzles or two fluid nozzles using air as the atomizing fluid were capable of producing water spray with 20 to 30μm MMD's. Because of the inherent simplicity of direct pressure nozzles and their much lower power requirements, only direct pressure nozzles were tested in detail. Preliminary tests using water as the test fluid indicated that the desired MMD could be produced by nozzles with orifices ranging from .005" diameter to .010" diameter operating at pressures between 21 kg/cm^2 (300 psi) and 42 kg/cm^2 (600 psi). Theoretical considerations indicated that the ammonium nitrate-urea-water solution, because of its lower surface tension (about 50 dynes per centimeter) and its higher density (about 1.3 g/cm^3) would produce a drop size distribution with an MMD of about 0.75X that produced by water.

Initial tests were conducted at 35 kg/cm^2 (500 psi) with brass nozzles having an initial orifice diameter of .007". The primary purpose of these initial tests was to determine the ability of the nozzle to atomize the fluid and to discover what difficulty, if any, would be encountered with nozzle clogging, nozzle erosion, and the solution salting out. Drop size distributions were also determined while these other tests were taking place. Tests were conducted using only 1 or 2 nozzles at a time since 2 nozzles always proved adequate to produce a very dense fog in the test chamber. Test procedures were to run the nozzles for a 5 to 10 minute period, shut the device down and let it sit for a period of time and then turn it on again. During a day of testing in this manner the nozzles did not clog, but some signs of chemical reaction with the brass were noted.

It was decided to shut the device down but not to flush or clean it in any way and to let it sit overnight. The following day the device was activated again and although the nozzles operated adequately for a period of time, the filters in the nozzle quickly clogged and collapsed, causing the nozzle orifices to be clogged. The nozzles were then removed and examined carefully under a microscope. It was found that the primary reason for the clogging was a sediment of undissolvable solids that was present in the commercial grade fertilizer. It was also determined that the nozzle orifices had been very badly eroded by the chemical action of the solution and had increased from their initial .007" diameter to as large as .015" diameter.

In all subsequent tests with the ammonium nitrate-urea-water solution the solution was carefully filtered to remove the undissolvable solids. It was found that approximately 5%

of the mass of the commercial grade fertilizer consisted of a clay-like undissolvable silt. No attempt was made to chemically analyze this silt. It was simply filtered out and discarded.

A total of 24 separate droplet samples were taken during the 35 kg/cm^2 (500 psi) atomization test. These were averaged in several different ways. One set of 12 samples was averaged to give the distribution shown in Fig. 1(a) with an MMD of 27μm. The second set of 12 samples was averaged to give the distribution shown in Fig. 1(b) with an MMD of 26μm. Then all 24 samples were averaged together as shown in Fig. 1 (c) and a best judgment smoothing of the size distribution made resulting in an MMD of 28μm. Since this MMD was obviously not equivalent to the average of the two separately determined MMD's, it was decided to do a second smoothing of the average of the size distribution from the 24 samples. This time the smoothing was biased in a reasonable way toward the smaller particles and a mass distribution was determined, giving an MMD of 24μm. The standard deviation of these four separate MMD determinations is 1.3μm. Thus it was decided that although an obvious error was introduced by the judgment factor used in smoothing the size distribution curve, this error would be acceptable. Other tests were conducted at 21 kg/cm^2 (300 psi) and at 42 kg/cm^2 (600 psi) with nozzles that became slightly eroded while the tests were being conducted. Results of the 21 kg/cm^2 tests are shown in Fig. 2(a) with an MMD of 25μm and of the 42 kg/cm^2 test in Fig. 2(b) with an MMD of 20μm.

After digesting the results of these tests another series of 22 samples was taken at a pressure of 28 kg/cm^2 (400 psi) with a .007" diameter orifice. In the 28 kg/cm^2 tests brass nozzles were still used but the orifice diameter was monitored very closely and new nozzles substituted whenever the slightest sign of erosion appeared. These samples were also averaged into 2 sets. One set of 12 samples with a total droplet count of 3600 produced an MMD of 18μm. Results are shown in Fig. 3(a). A second set of 10 samples with a total count of 10 000 droplets gave an MMD of 16μm as shown in Fig. 3(b). All 22 samples were then averaged together, producing an MMD of 16μm as shown in Fig. 3(c).

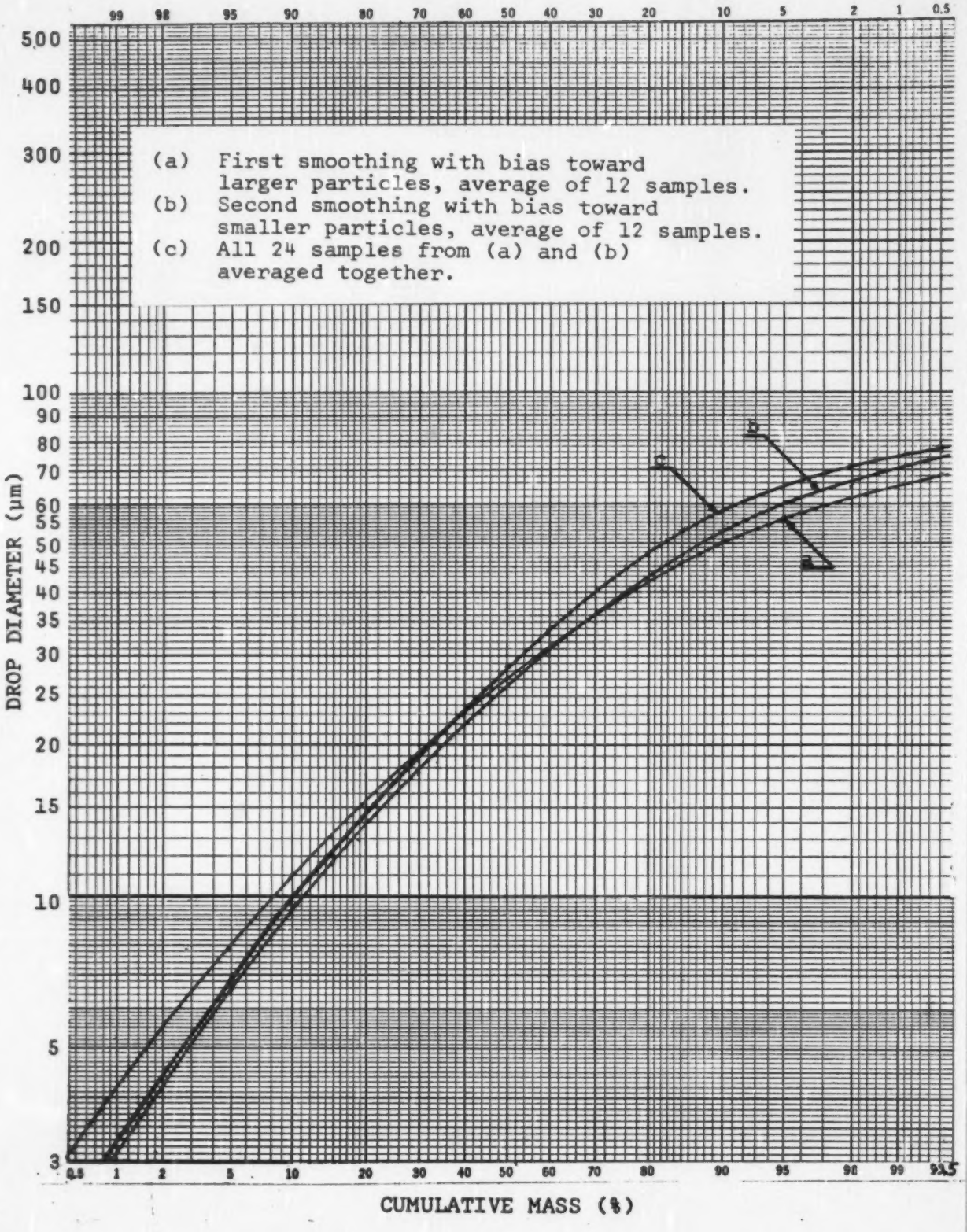

FIG. 1 RESULTS OF INITIAL FOG CHAMBER ATOMIZATION TESTS WITH AMMONIUM NITRATE-UREA SOLUTION. PRESSURE 35 kg/cm^2 (500 psi). (BRASS ORIFICES BECAME BADLY ERODED DURING TESTS).

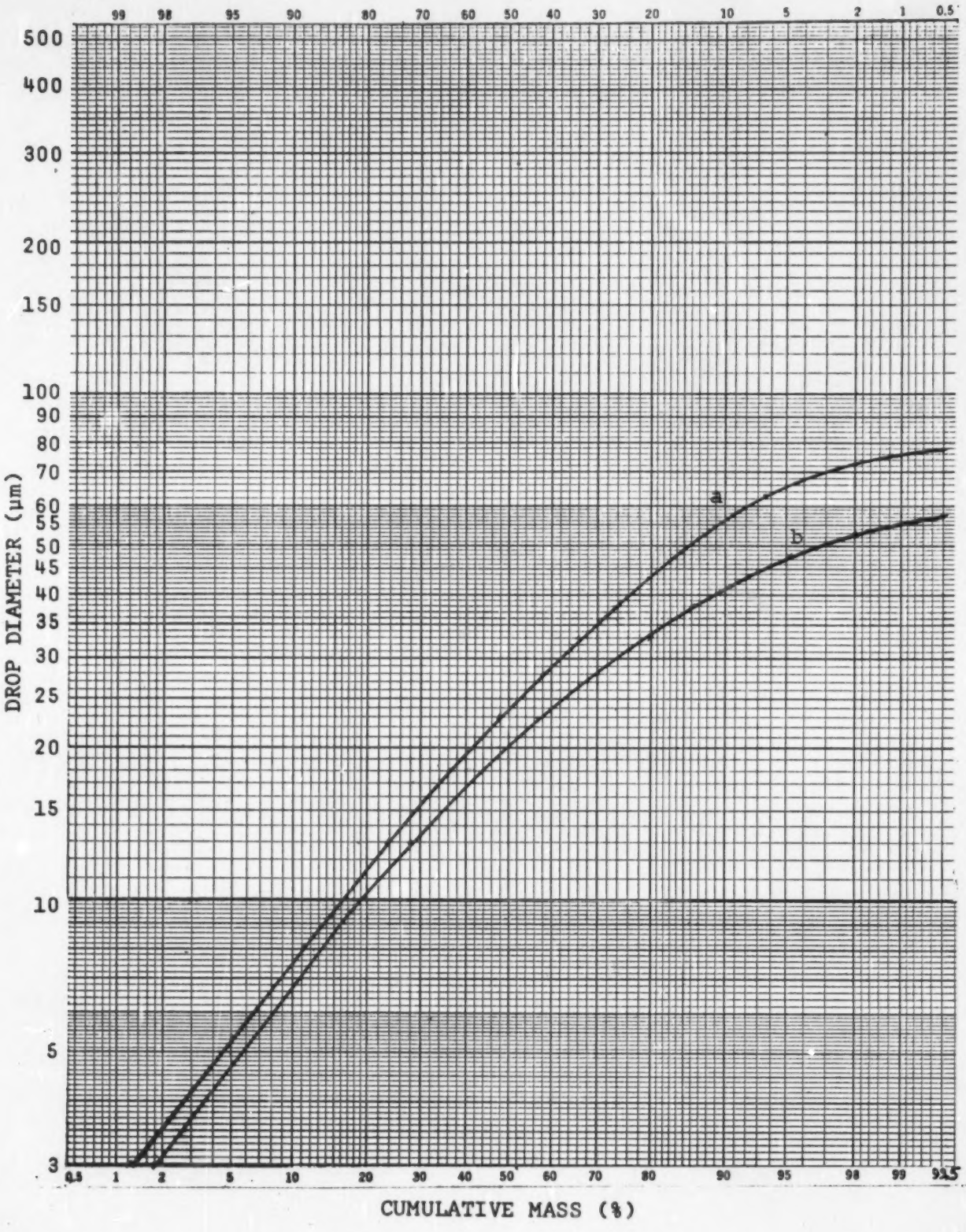

FIG. 2 FOG CHAMBER ATOMIZATION TESTS AT (a) 21 kg/cm^2 (300 psi) AND (b) 42 kg/cm^2 (600 psi). BRASS ORIFICES BECAME SLIGHTLY ERODED DURING TESTS.

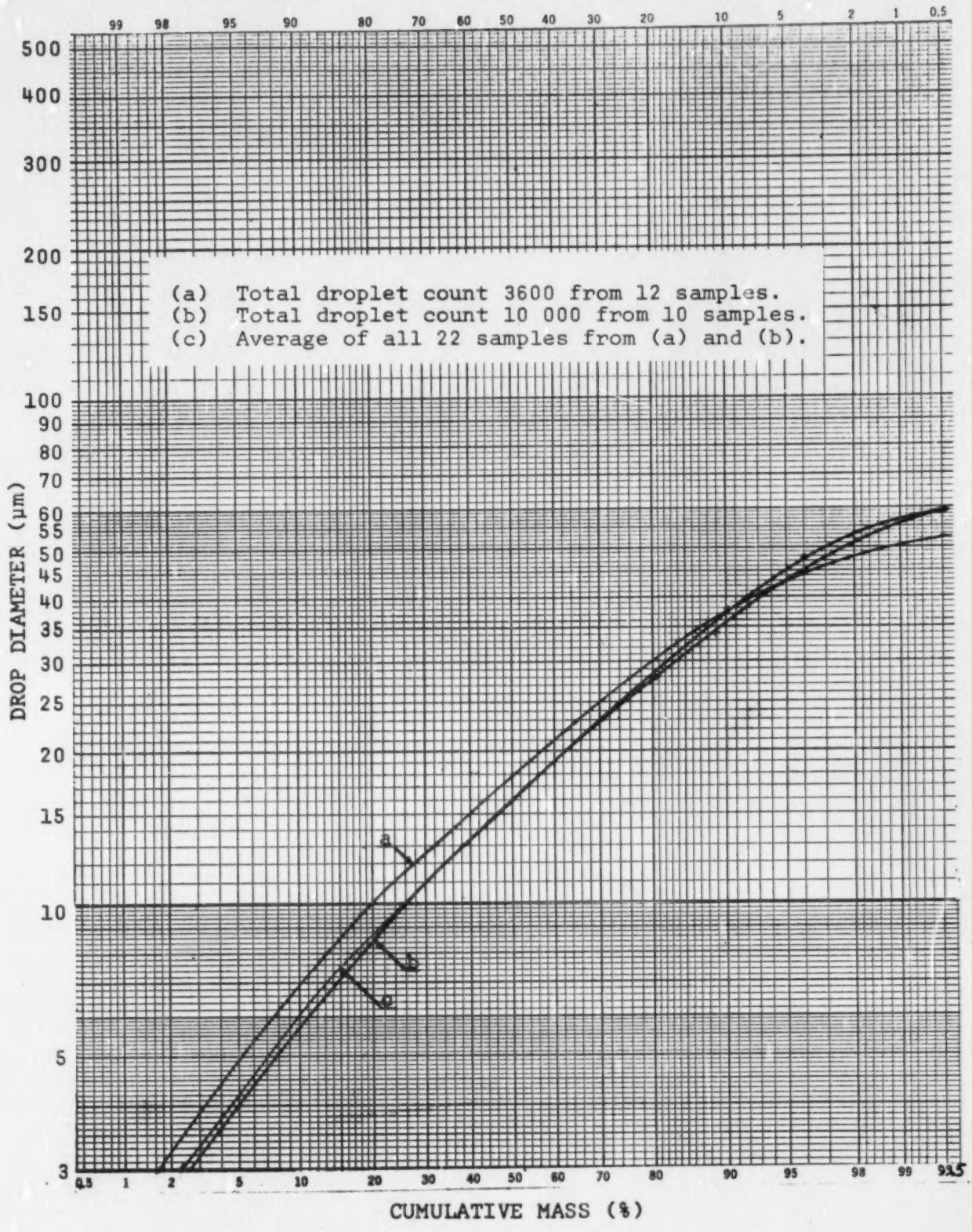

FIG. 3 FOG CHAMBER ATOMIZATION TESTS AT 28 kg/cm^2 (400 psi). NO SIGNIFICANT ORIFICE EROSION.

4. Nozzle Erosion Tests

After it became evident that brass was not a compatible material for use with ammonium nitrate-urea solutions, some additional tests were run using stainless steel nozzles to see what erosion, if any, would take place. The nozzles were operated under conditions similar to those described in the 35 kg/cm^2 tests except that filtered solutions were used so that clogging would not be a problem. Over a period of several days of soaking in the solution and randomly turning the system on and off, no change whatsoever was noted with the stainless steel nozzles. To obtain further information about materials compatibility, Dr. Pierre St. Amand and Dr. Bill Finnegan of NOTS, China Lake, were consulted. They confirmed our findings about brass and stainless steel and also pointed out that in their tests aluminum had proved to be a suitable material for use with the solutions. The following table is taken from their report.[1]

CORROSION OF VARIOUS TEST MATERIALS BY AN EQUIMOLAR AMMONIUM NITRATE-UREA-WATER SOLUTION

Test Specimen	Inhibitor added to Solution	Weight Loss $g/cm^2/hr \times 10^6$
Magnesium alloy, AZ31B	None	738
	1.6% thiourea & .8% K_3PO_4	1114
Brass	None	111
	1% thiourea	8
Mild Steel	None	28
	1% thiourea	0.45
Chromium plated Steel	None	1.3
	1% thiourea	4.7
Cadmium plated Steel	None	247
Aluminum	None	0
	1% thiourea	0
Lacquers & Enamels	None	No visible effects

[1] Project Foggy Cloud III, Phase I, Tommy L. Wright, Richard S. Clark and Pierre St. Amand, Naval Weapons Center, China Lake, California, April 1972.

5. Tests of a Spinning Cylinder Device

A Beecomist Model 350 spinning cylinder device was tested to determine the drop size distribution and mass median diameter of the droplets produced. The literature furnished by Beecomist did not specify the droplet size but simply said that small droplets were produced. The literature did, however, imply that by varying the sieve size of the sintered metal cylinder between the 20 and 100μm sieve sizes available, either larger or smaller droplets would be produced. That is incorrect and, in fact, sieve size has nothing to do with the size of particle produced as long as the pore size is significantly below the size of the theoretically smallest particles that will be produced. The particle size is determined only by the peripheral speed of the cylinder, by the surface tension and density of the fluid, and by the feed rate of the fluid if the feed rate is above a certain minimum. Too rapid a fluid feed rate will produce particles that are much larger than are theoretically possible with the device. The theory and experimental results of atomizing with spinning cylinders is discussed in great detail in a report by Mee and Hage.[1]

In that report it was demonstrated that with low enough feed rates spinning cylinder devices could be made to produce single size particles and that the diameter of the droplets produced could be accurately predicted by the following formula:

$$d = K(T/\rho D)^{\frac{1}{2}}\omega^{-1}$$

Where

d = drop diameter

K = a constant (typically varies between 3 and 5 depending upon cylinder RPM and fluid used)

T = surface tension of the fluid

D = cylinder diameter

ρ = density of the fluid

ω = angular speed of the cylinder

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[1] Development of the Theoretical and Technological Prerequisites to Field Investigation of Particulate Agent Behavior, Keith D. Hage and Thomas R. Mee, June 1966, Contract DA-18-035-AMC-399(A) The Travelers Research Center, Inc.

The above formula also serves to give an indication of MMD when feed rates that are higher than those required to produce single size particles are used. The formula indicates that the Beecomist Model 350 with a cylinder diameter of 3-1/2" and a motor speed of 7000 rpm could theoretically produce water droplets with an MMD of 150μm. The same theory predicts that ammonium nitrate-urea-water solution droplets would be about 75% the diameter of water droplets.

The particle sizes are obviously much larger than the 20 to 30μm particles desired. Nevertheless two sets of experiments were conducted with the Beecomist using water as the test fluid. When the device was operated at the manufacturer's recommended flow rate of 4 gpm, a spray with particles ranging from approximately 30 to 350μm diameter was produced. The spray had an MMD of about 250μm, as is shown in Fig. 4(a). Another set of tests was conducted at the flow rate of 0.5 gpm. At this lower flow rate the device produced a spray with an MMD of 200μm. The 0.5 gpm results are plotted in Fig. 4(b).

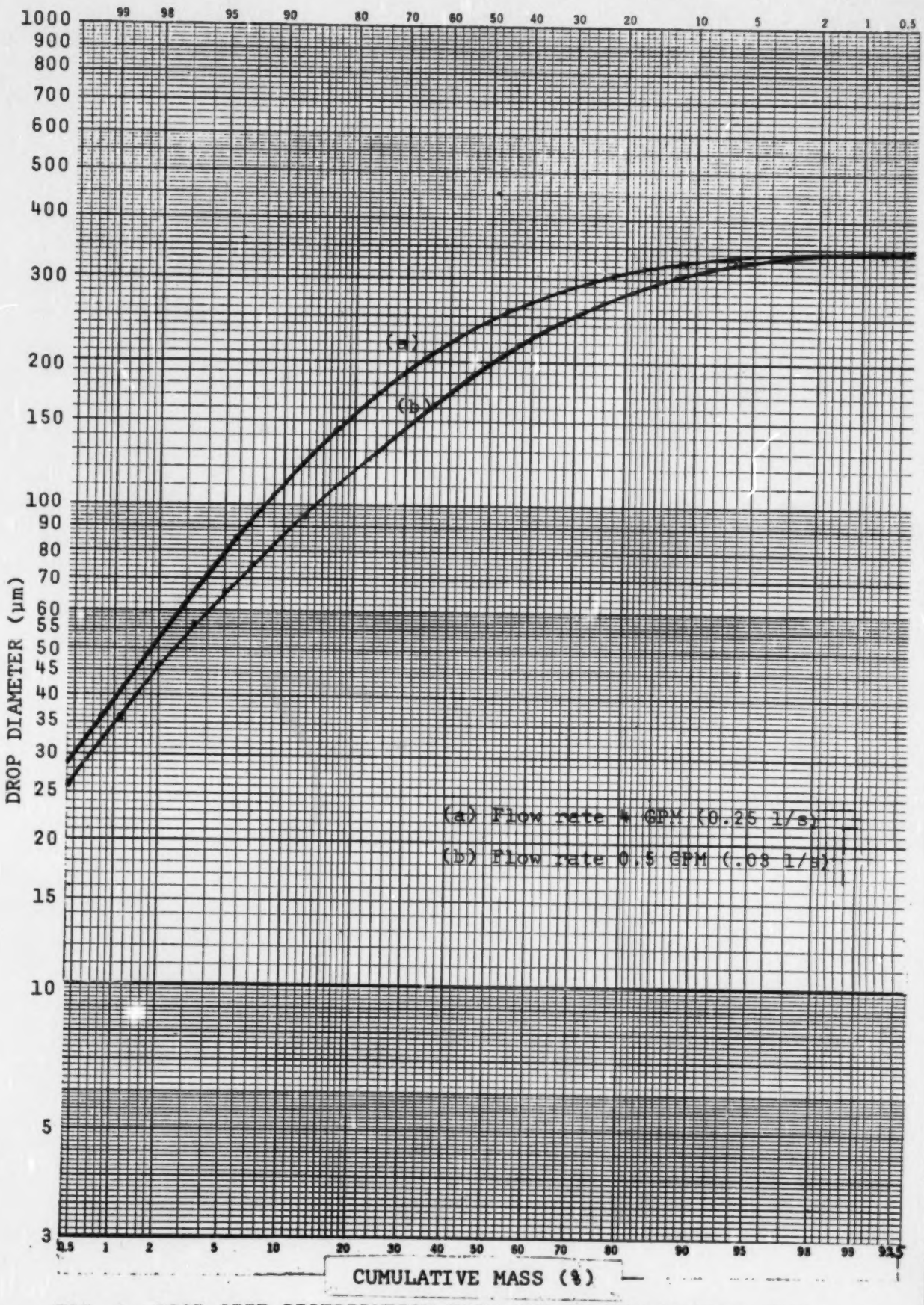


FIG. 4 DROP SIZE DISTRIBUTION FROM THE BEECOMIST MODEL 350 SPINNING CYLINDER ATOMIZING WATER UNDER STATIC, NO WIND CONDITIONS

STAGE II

DETERMINATION OF AN OPTIMUM ATOMIZATION DEVICE FOR AN IN-FLIGHT SYSTEM

1. Atomization Test Procedures in a 110 m/s Air Stream

To simulate in-flight conditions an experimental test setup was built consisting of a high velocity blower directing a 110 meter per second (250 mph) air stream over the atomization device being tested. The experimental setup is shown schematically in Fig. 5.

In the original planning of the project it was thought that the atomization tests would be conducted in a "sing around" type wind tunnel. This "standard type" wind tunnel has the exhaust air ducted back to the intake of the tunnel to reduce the power requirements for moving the air stream. After further consideration it was decided that it would be virtually impossible to filter all aerosol particles from the return flow and thus incorrect size distributions would be attained. The test procedure depicted in Fig. 5 eliminated this problem.

The blower used, a Clemens Mfg. Co. Model HP3, was selected because the manufacturer specified that the blower had an exit velocity of approximately 110 meters/second. All atomization devices tested were exposed to this high velocity air stream just as it exited from the mouth of the blower orifice. Velocities at the test point were verified by measuring the velocity profile at the test point with a pitot-static air velocity instrument borrowed from an aircraft. The velocity profile was found to be a constant 110 meters per second across the zone where the atomization devices were exposed.

In analyzing a given device, tests were usually conducted both under static conditions and in the high velocity air stream, using both fresh water as a test fluid and solutions of ammonium nitrate and urea. All solution tests were conducted with a mixture containing approximately 44.1% ammonium nitrate (by weight), 35.4% urea, and 20.4% water. The density of this solution was 1.32 g/cm^3, viscosity under the conditions of the tests was approximately 5 centipoise, and surface tension was approximately 50 dynes. (See Fig. 6). Since the experimental procedures were much simpler when fresh water was used, it was typical to conduct a few tests using water to confirm that the experimental setup and test procedures were adequate and then use solution as the test fluid for the majority of the tests.

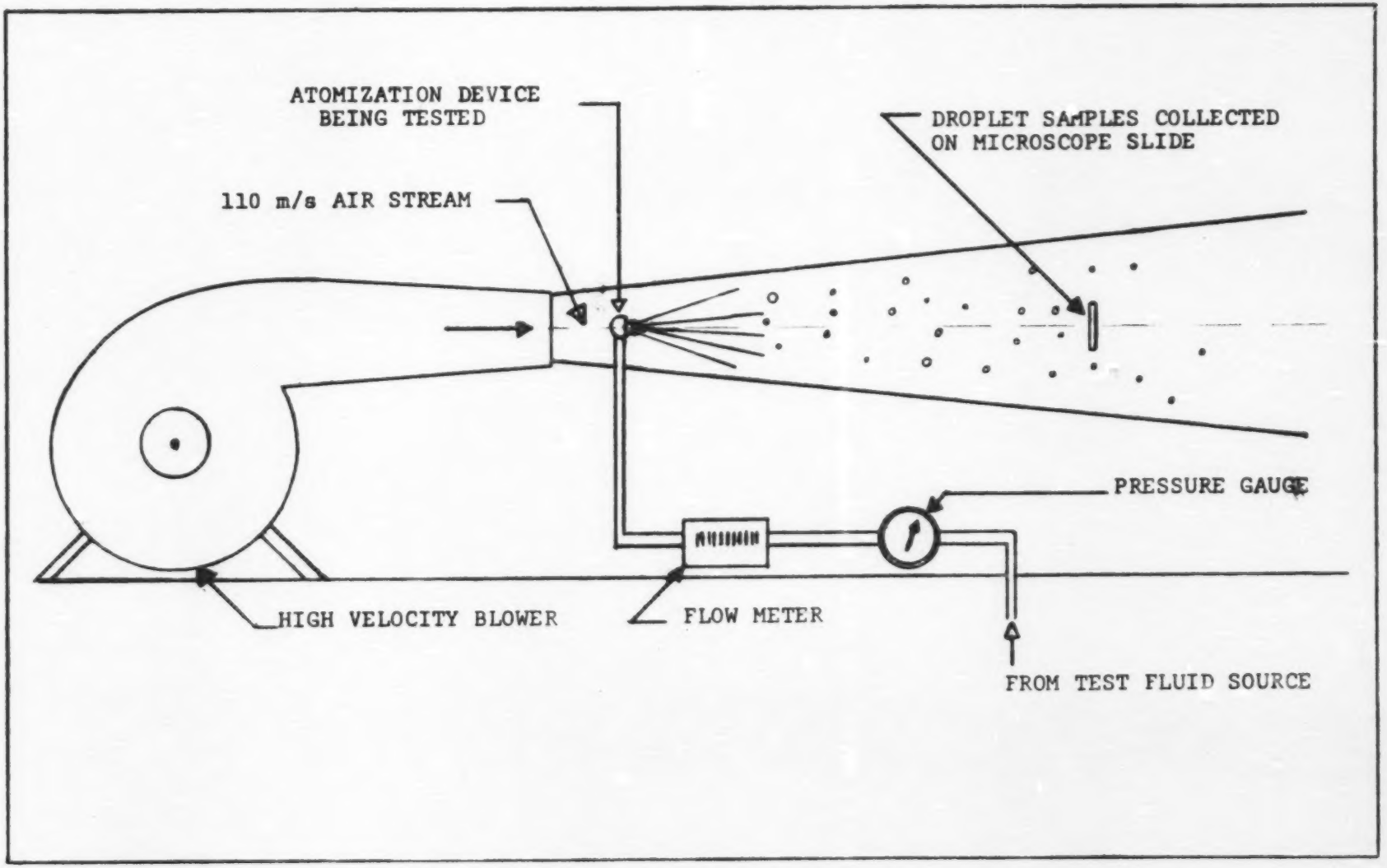


FIG. 5 SCHEMATIC REPRESENTATION OF TEST SET-UP FOR HIGH VELOCITY AIR STREAM ATOMIZATION EXPERIMENTS

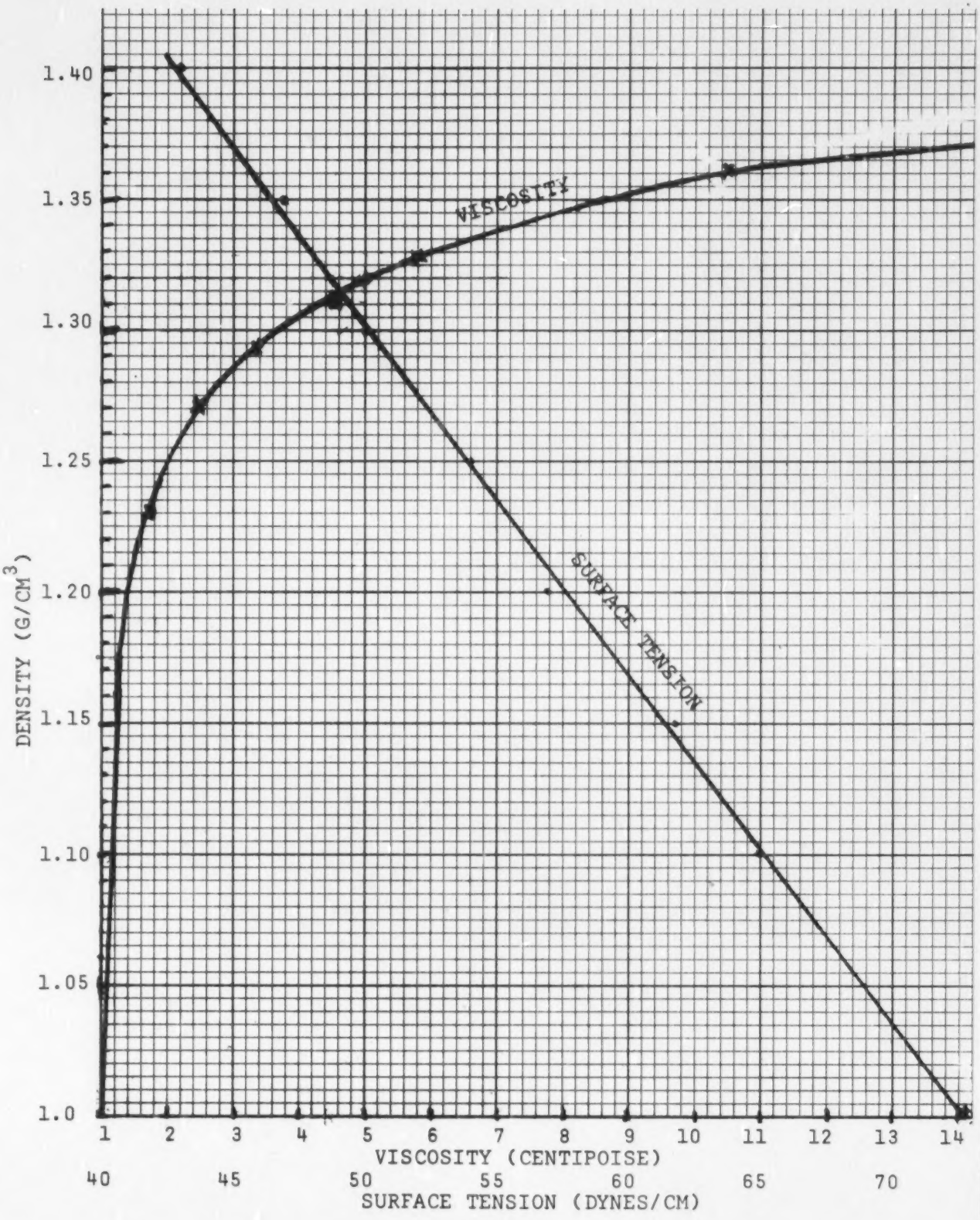


FIG. 6 SURFACE TENSION AND VISCOSITY FOR AMMONIUM NITRATE/ UREA SOLUTIONS

Aerosol sampling was accomplished by exposing a silicone fluid coated microscope slide to the air stream containing the aerosol particles. This slide was attached to the end of a rod approximately 1 meter in length and whipped through the visible plume of droplets from the device being tested. The sampling was done at a distance approximately 2 meters downstream from the device being tested at a point where the plume velocity had expanded and slowed considerably. This sampling distance was determined experimentally as the distance where the stream velocity was slow enough so as not to blast the silicone fluid from the surface of the slide. It was found that if the sample slides were exposed too close to the atomizing device where stream velocities were still quite high, several problems arose. Not only was the silicone fluid blasted off the slide, but droplets impinging at high velocities would coalesce with each other and thereby give a false determination of the drop size distribution. The whipping technique was tested in some detail during Stage I of the project and was found to have 100% collection efficiencies for particles larger than about 25μm. By comparing whip samples with samples collected by gravity settling, which has a 100% collection efficiency for small droplets, the collection efficiency of the whip technique was determined and appropriate correction factors determined for the whip technique. These correction factors are listed below.

CORRECTION FACTORS FOR WHIP SAMPLING

Particle Diameter	Multiplication Factor
25μm and larger	1.0 X
20-25	1.1
15-20	2.1
10-15	6.25
5-10	20.0

These factors were used where appropriate to correct for the collection efficiency of the whip sampling technique.

The experiments in Stage I were mostly conducted with atomization devices producing droplets smaller than 50μm. Many of the tests were conducted using water as the atomization fluid. During the tests the sampling slides were coated with a silicone fluid having a density of approximately 1 g/cm^3. However, during Stage II when atomization devices producing droplets several hundred microns in diameter were

being tested, it was found that the larger solution droplets would settle quite rapidly through the silicone fluid and spread onto the top of the microscope slide. To correct this difficulty a silicone fluid with a density of 1.3 g/cm^3 was used and the settling out problem was eliminated.

The same sampling and counting procedures developed during Stage I were used for all tests conducted during Stage II. For any given test approximately 10 to 12 samples would be taken and photographed with a microscope using 35mm black and white film. Each sample photograph would typically contain 100 to 300 droplets. After the negatives were developed images of the droplets would be projected on a screen at 500X magnification. All droplets would then be counted, measured and tabulated into 5µm intervals on a drop size distribution worksheet. From these worksheets a graph showing the number of droplets in each 5µm size interval would be plotted. A smoothed curve would be plotted through these data points and from this smoothed curve the mass of particles in each size category was calculated and from this information the mass median diameter determined. These sampling and sizing techniques are described in greater detail in the Stage I report where it was demonstrated that the standard deviation among samples was always less than 2µm.

2. Tests of Two-Fluid Air Jet Nozzles

Two nozzles were tested; one manufactured by the Sonic Development Corp. and called the Sonicore nozzle, and one developed by Mr. William E. C. Eustis. The Sonicore nozzle was found to produce smaller particles but required approximately twice the amount of air flow as the Eustis nozzle. The Sonicore device could easily produce water droplets with an MMD of 20μm or less whereas the Eustis device was only capable of producing water droplets as small as an MMD of 40μm. The Eustis nozzle was tested in greater detail because of its more efficient use of air. Results of these tests are plotted in Fig. 7.

The Eustis nozzle that was loaned for testing purposes was of brass construction so most tests had to be conducted using water so as not to destroy the nozzle by the corrosive effects of the solution mixture. From tests with other atomization devices it was demonstrated that the MMD of solution droplets would be approximately 75% that of water droplets. If it is assumed that the same ratio would apply for the Eustis nozzle, then it can be predicted that 30μm MMD solution droplets could be produced at 7 kg/cm^2 (100 psi) air pressure. The 75% correction factor was demonstrated to be approximately correct by the one solution atomization test that was conducted. This test was conducted at 4.2 kg/cm^2 with a solution flow rate of 2.5 ml/s. The tests resulted in an MMD of 36μm as compared to 38μm predicted by the 75% method. Thus it is felt that the MMD solution curve shown in Fig. 2 is approximately correct. The mass distributions for several points on the curve of Fig. 7 are given in Fig. 8.

To atomize solution and produce 30μm MMD droplets at a rate of 2 liters per second (30 gpm) would require approximately 760 Eustis nozzles operating at 7 kg/cm^2 (100 psi) and consuming approximately 566 liters per second (1200 cfm) of air. To pump this amount of air would require approximately 200 HP at sea level and 300 HP at 10 000 ft.

By contrast, to produce 20μm MMD droplets with the Sonicore device at 2 liters per second (30 gpm) would require approximately 900 nozzles operating at 5.6 kg/cm^2 air pressure and consuming approximately 1486 liters/sec. of air. To pump air at this rate would require approximately 650 HP at 10 000 ft.

The horsepower requirements for air compressors were estimated using the following equation:

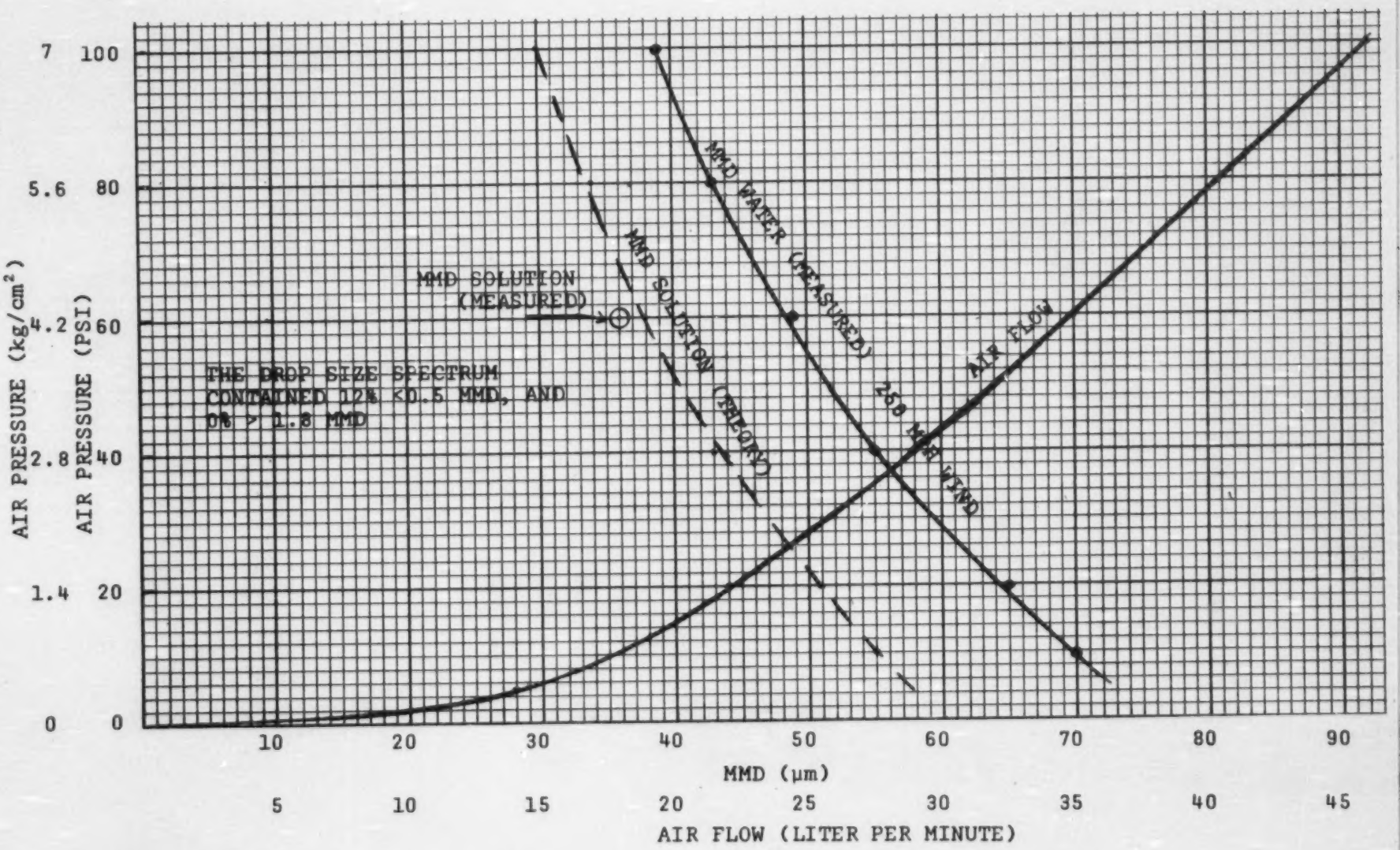


FIG. 7 DROP SIZE AND AIR FLOW RATE FOR THE EUSTIS TWO FLUID NOZZLE (MMD's WERE DETERMINED AT A FLUID FLOW RATE OF 2.5 ML/S)

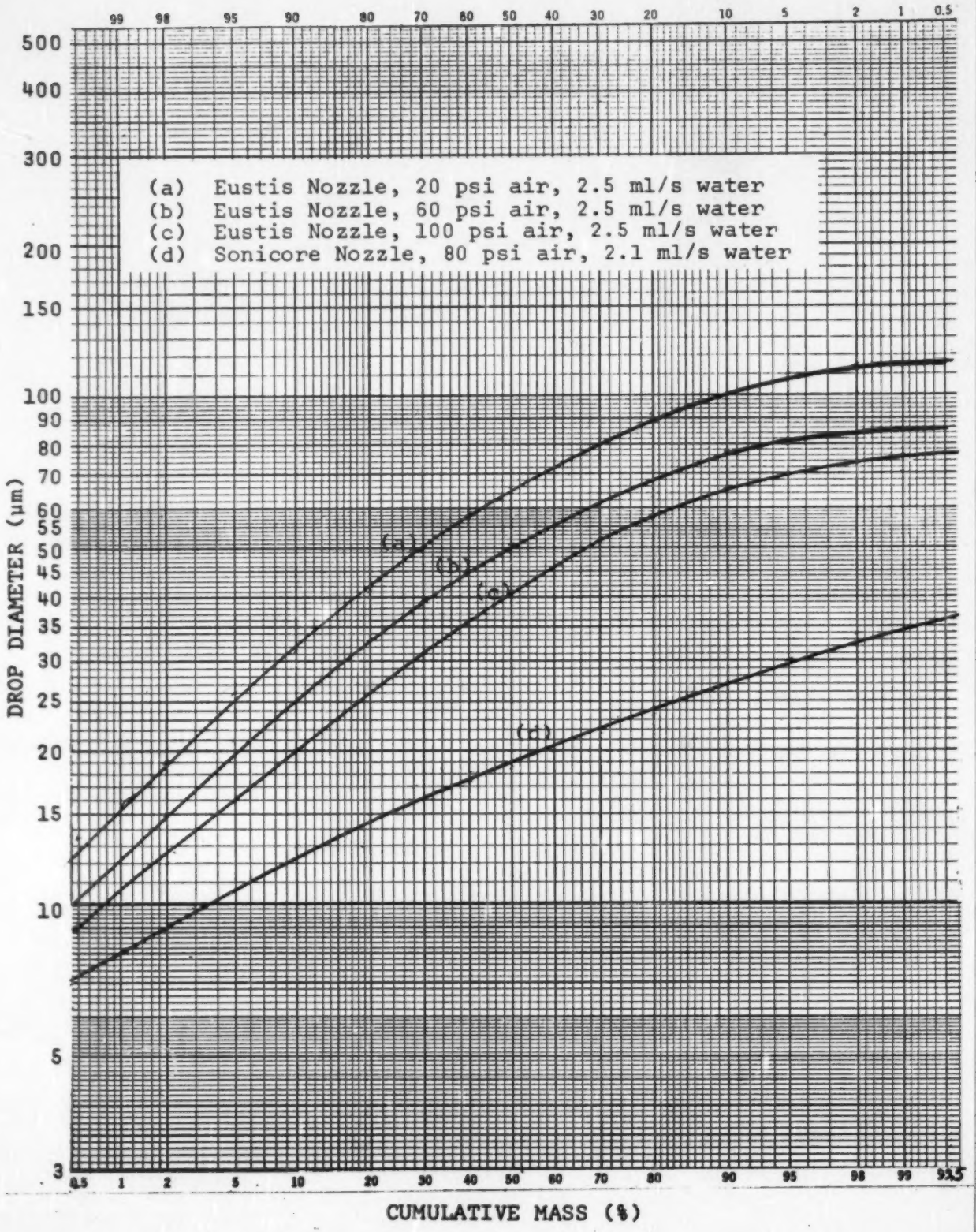


FIG. 8 DROPLET SIZE DISTRIBUTION FOR THE EUSTIS AND THE SONICORE TWO FLUID NOZZLES

$$H.P. = CFM \times 0.23184 \{(1.13\ P_2/P_1)^{0.286}-1\}$$

where: H.P. = Horsepower required

CFM = air flow in cubic feet per minute

P_1 = ambient atmospheric pressure

P_2 = output pressure of the compressor

A discussion of this equation is given on page 14-46 in the Standard Handbook for Mechanical Engineers by Baumeister and Marks, 7th Edition, McGraw-Hill.

3. Tests of Spinning Cylinder Devices

In the initial test during Stage I a Beecomist Model 350 spinning cylinder operating at 7 000 rpm was tested. The device was found to produce water droplets with an MMD of 350μm under static conditions. During Stage II a spinning cylinder device built by Mee Industries Inc. and capable of operating at up to 24 000 rpm was tested. The tests were conducted under both static conditions and in a 250 mph air stream using both water and solution fluids. The cylinder was sintered bronze with a 20μm pore size. It was 3.8 centimeters diameter and 10 cm in length. Fluid was fed to the inner surface of the cylinder at 0.25 gpm (16 ml/s). Under static conditions a solution aerosol with an MMD of 58μm was produced. In a 110 meter per second air stream with the air flow parallel to the spinning axis of the cylinder, the MMD was reduced to 41μm. Using water as the fluid the MMD's were 98μm in still air and 70μm in the 110 meter per second air stream. Results are summarized below and mass distributions are given in Fig. 9.

MMD OF DROPLETS PRODUCED BY 24,000 RPM CYLINDER

	WATER	SOLUTION
Still Air	98μm	58μm
110 m/s Air Stream	70μm	41μm

Theory predicts that

$$MMD = K(T/\rho D)^{\frac{1}{2}}\omega^{-1}$$

where T = surface tension of the fluid

D = cylinder diameter

ρ = density of the fluid

ω = angular speed of the cylinder

For a solution with a density of 1.32 g/cm^3 K turns out to be 4.87. Using this constant in the above equation it can be predicted that to produce 20μm MMD solution droplets would require approximately 71 500 rpm. The cylinder tested required 0.2 HP to drive at 24 000 rpm and produce droplets in the 40-50μm MMD range. To achieve a flow rate of 2 liters per second (30 gpm) would require 120 such devices giving a total power consumption of 24 HP. It most likely would take more power to achieve the higher rpm necessary to produce smaller droplets but no estimate was attempted of these requirements.

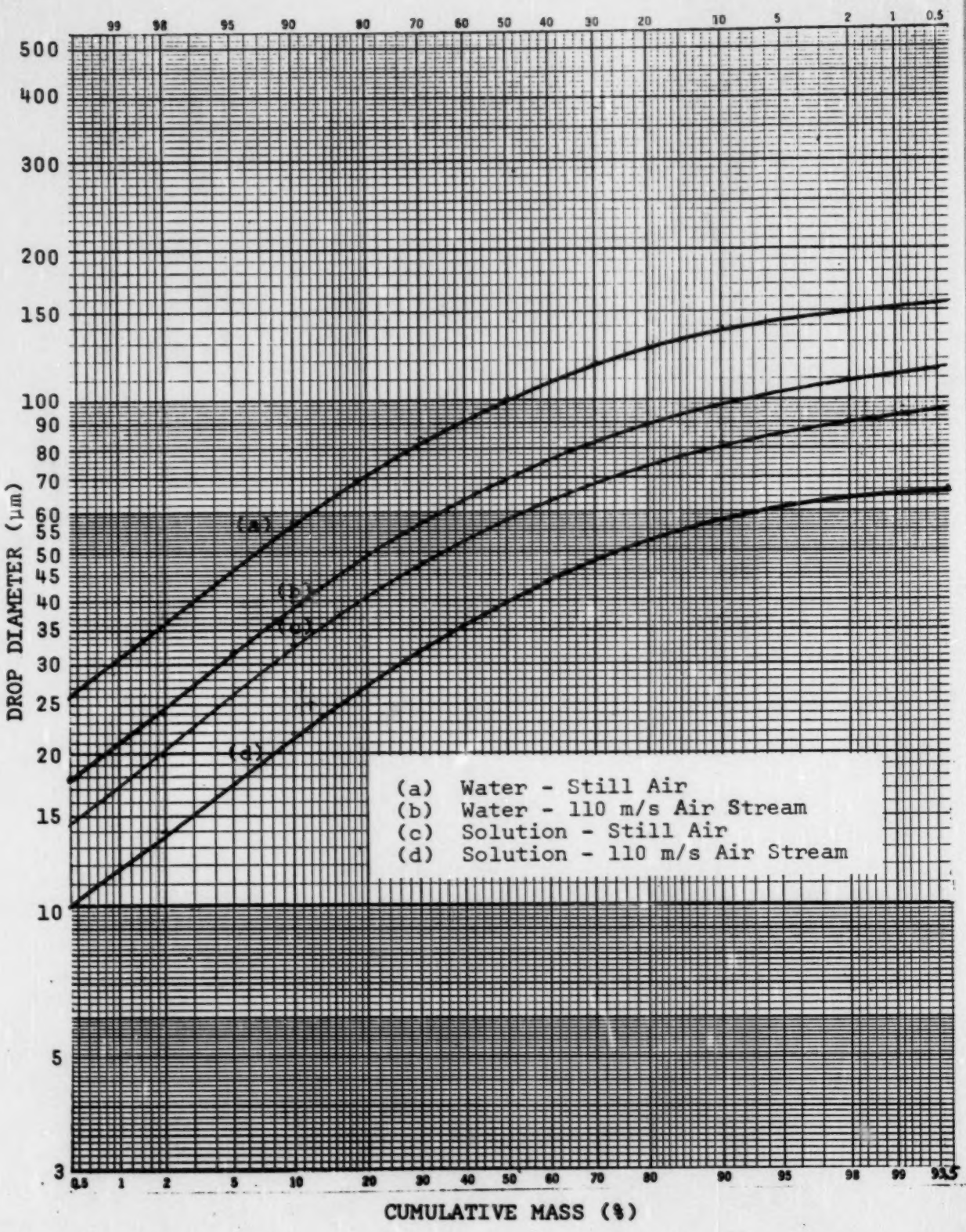

DROP DIAMETER (μm)
CUMULATIVE MASS (%)
(a) Water - Still Air
(b) Water - 110 m/s Air Stream
(c) Solution - Still Air
(d) Solution - 110 m/s Air Stream

FIG. 9 DROPLET SIZE DISTRIBUTION FOR THE MEE SPINNING CYLINDER DEVICE

4. Tests of Direct Pressure Impaction Type Nozzles

Because of the low power requirements and simplicity of the nozzles, it was felt that direct pressure nozzles would best solve the needs of the project. Extensive tests were conducted in the 110 m/s air stream and several nozzles were selected that could produce solution droplets in the desired size ranges. For example it was found that a nozzle with a 0.178mm (.007") orifice diameter could produce droplets with MMD's of 20-30μm. Nozzles with orifices between .020" (0.508mm) and .030" (0.762mm) can produce droplets with MMD's in the range of 50-100μm, and orifice diameters from .040" (1.02mm) and .070" (1.78mm) can produce droplets in the 100-200μm MMD range. For a given nozzle the MMD can be varied by changing the operating pressure between approximately 14 kg/cm^2 and 46 kg/cm^2. Results of the air stream tests are summarized in Fig. 10 and some selected mass distributions are shown in Fig. 11.

Horsepower requirements for atomizing two liters per second (30 gpm) will vary between approximately 14 HP and 22 HP depending upon the efficiency of the pump used. The horsepower equation has a form of:

$$H.P. = \frac{GPM \times PSI}{C}$$

where the Constant C contains a number for the efficiency of the pump.

For direct pressure nozzles the power requirements are totally independent of the drop size being produced and depends only upon the flow rate and the pressure required.

Drop size distributions for these nozzles were determined in still air and with the nozzles oriented in various ways in the air stream. In the air stream tests it was found that it was totally impractical to face the nozzles directly into the air blast since the spray was then blown back into the structure of the nozzle itself and totally unpredictable and uncontrollable atomization occurred. Tests were also conducted with the nozzles oriented 90° to the direction of air flow; and with the nozzles facing downstream, thus affording some protection from the direct blast of air onto the nozzle orifice opening.

Somewhat surprising results were obtained when the nozzles were oriented at 90° to the direction of the air flow. Under these conditions the air blast was directly across the orifice opening and had a very disturbing effect on the spray pattern before complete atomization had taken place. The effects of the air blast were not so apparent when small droplets were

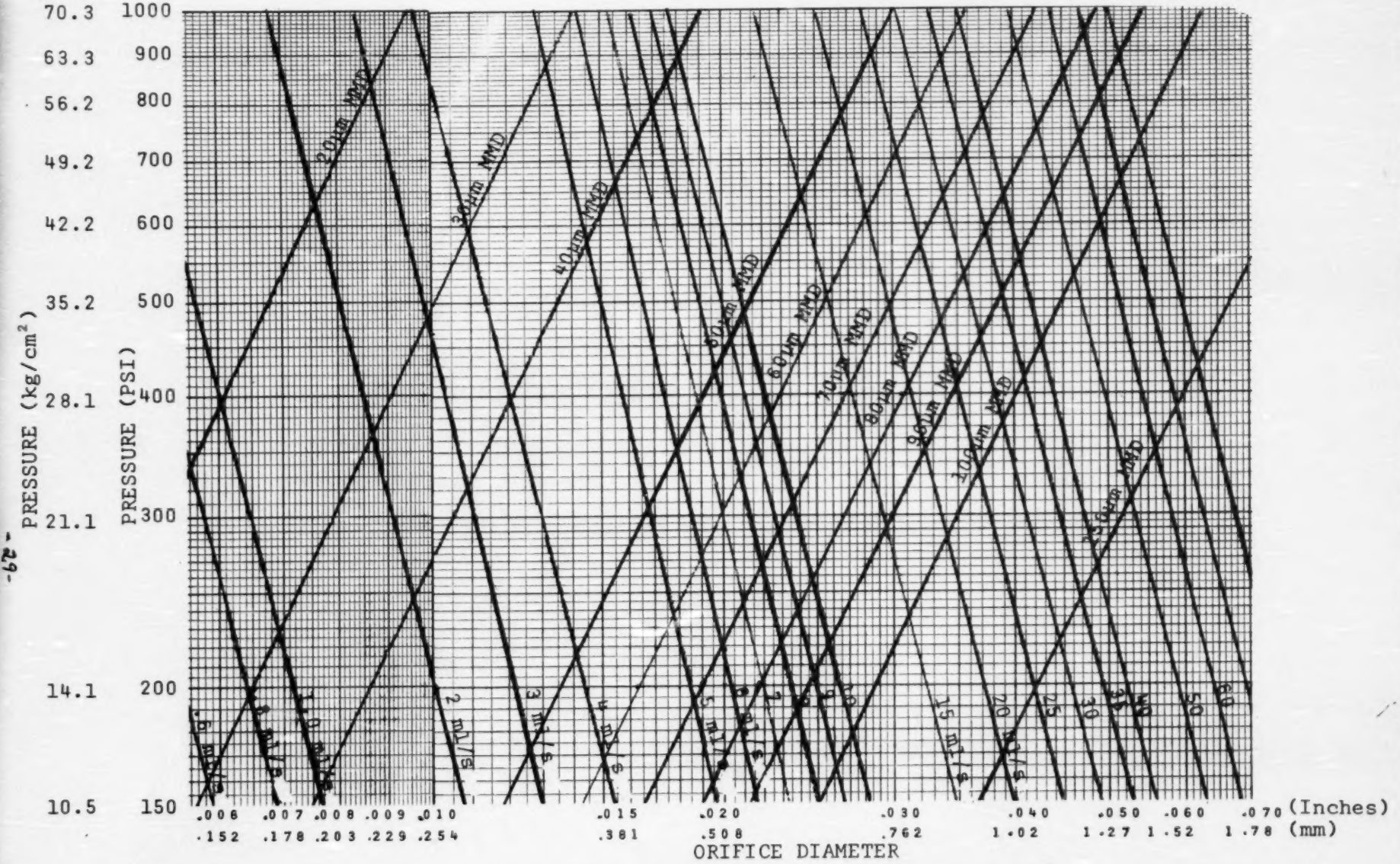


FIG. 10 OPERATING CHARACTERISTICS OF DIRECT PRESSURE IMPACTION TYPE NOZZLES ATOMIZING AMMONIUM NITRATE/UREA SOLUTIONS (1.32 g/cm³ density) IN A 110 m/s AIRSTREAM

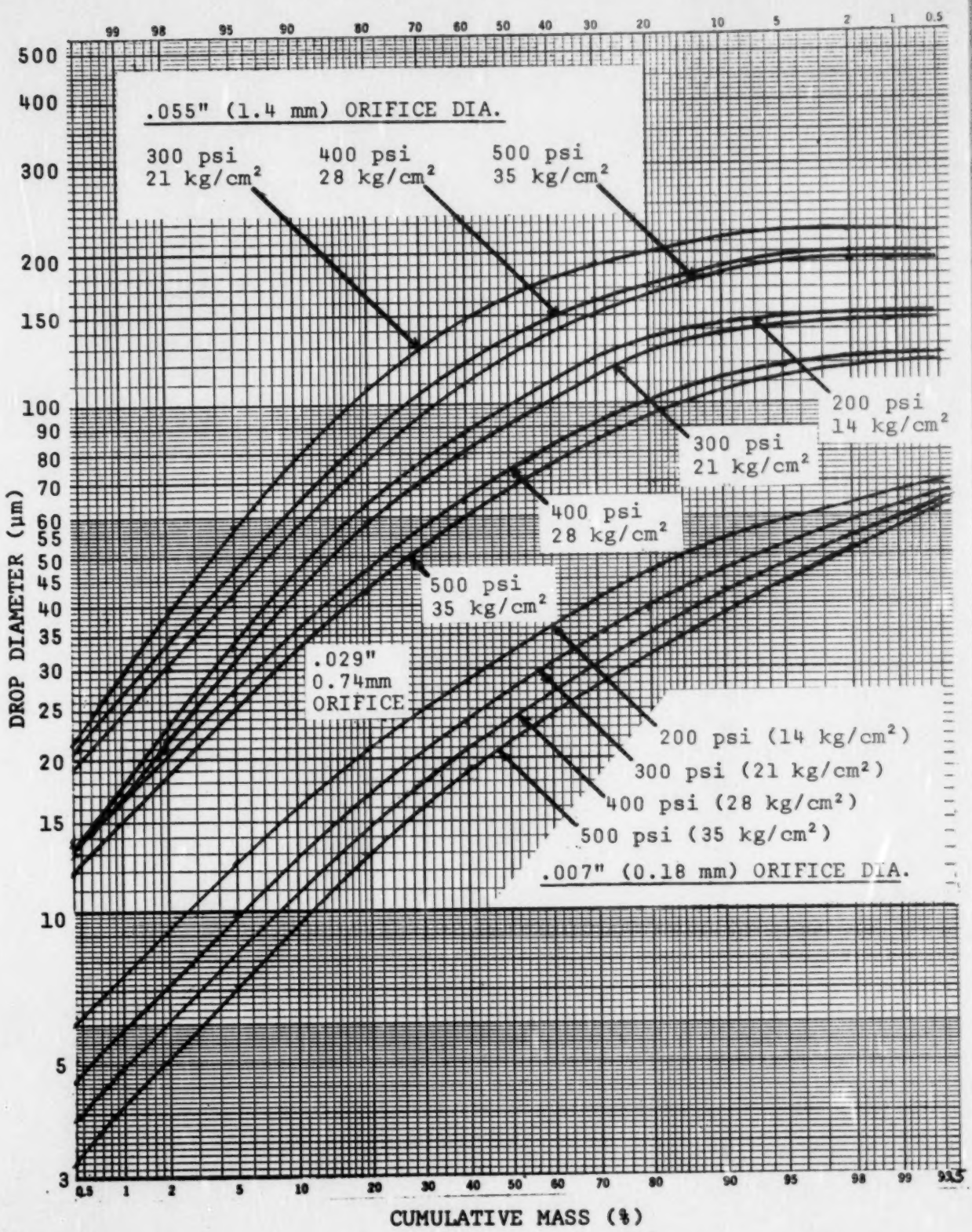


FIG. 11 DROPLET SIZE DISTRIBUTION FOR IMPACTION TYPE NOZZLES ATOMIZING AMMONIUM NITRATE-UREA SOLUTION IN A 110 METERS PER SECOND AIR STREAM

being produced as when large droplets were being produced. The results showed that if water was used as the fluid the resulting MMD in the air blast was larger than that produced under static conditions, but that if solution was used as the fluid, the resulting MMD in the air blast was smaller than that produced under static conditions.

For example, a nozzle with a .040" diameter orifice opening at 35 kg/cm^2 (500 psi) under static conditions will produce water droplets with an MMD of approximately 130μm. When oriented 90° to a 110 m/s air stream that same nozzle produced water droplets with an MMD of 166μm. That same nozzle at 35 kg/cm^2 will produce solution droplets with an MMD of approximately 85μm under static conditions, but will produce solution droplets with an MMD of approximately 70μm when oriented 90° to the air stream. It was also found that with nozzles in this orientation the MMD did not change much with fluid pressure but only with the size of the orifice opening. The test results were very erratic and unpredictable but in general, for example, a .040" nozzle would produce approximately the same MMD at 14 kg/cm^2 (200 psi) as it would at 35 kg/cm^2 (500 psi).

The fact that water droplets got larger in the air blast whereas solution droplets got smaller is probably explainable by the difference in the surface tensions of the two fluids. Water has a surface tension of approximately 73 dynes whereas the solution at the densities used in this test has a surface tension of approximately 45 dynes/cm. (Surface tension and viscosity for various density solutions were measured and are depicted in Fig. 6).

Direct pressure nozzles atomize fluids by ejecting the fluid through a rounded orifice and then spreading it in an expanding conical shape which then breaks up into wavelets and eventually into droplets. When the air stream is directed across the orifice at 90° to the direction of the orifice opening, globs of fluid are ripped from the expanding cone before it has a chance to break into droplets as it normally would under static conditions. With a high surface tension fluid such as water these globs pull together into larger droplets than they would if the expanding cone were allowed to break up without being disturbed by the high velocity air stream. Low surface tension fluids, on the other hand, tend to be broken into smaller particles because the added energy of the air stream causes the globs to break up into globlets. Although the atomization process was helped somewhat by the high velocity air stream, it proved to be a disadvantage because the results were erratic and therefore unpredictable.

It was found that by protecting the nozzle orifice from direct impingement of the air stream more predictable results could be obtained. The amount of protection needed was very small and simply facing the nozzles downstream proved adequate. In the air stream the perturbation in the drop size spectrum for the .007" orifice nozzle was almost negligible. For the larger orifice nozzles the MMD's were reduced by approximately 10 to 15% but in a very consistent manner. Thus an orifice size could be chosen that will produce droplets somewhere within the desired range, and by simply varying the pressure of the fluid MMD's can be controlled in a predictable manner.

5. Description of Direct Pressure Impact-Type Nozzles

One version of an impact-type nozzle is shown in Fig. 12. These nozzles are also commonly known as pin jet nozzles because of their mode of operation.

In operation high pressure fluid is forced through the orifice opening forming a high velocity cylindrical stream of fluid which then impacts onto the pin surface opposing the orifice opening. When this impact pin is properly aligned it causes a sheet of fluid to spread from the impact point as an expanding hollow cone. As the sheet of fluid spreads it also thins out very rapidly and ripples and turbulence that form in the sheet cause it to break up into droplets. For a given fluid the size of the droplets that form is proportional to the diameter of the jet and inversely proportional to the velocity of the jet.

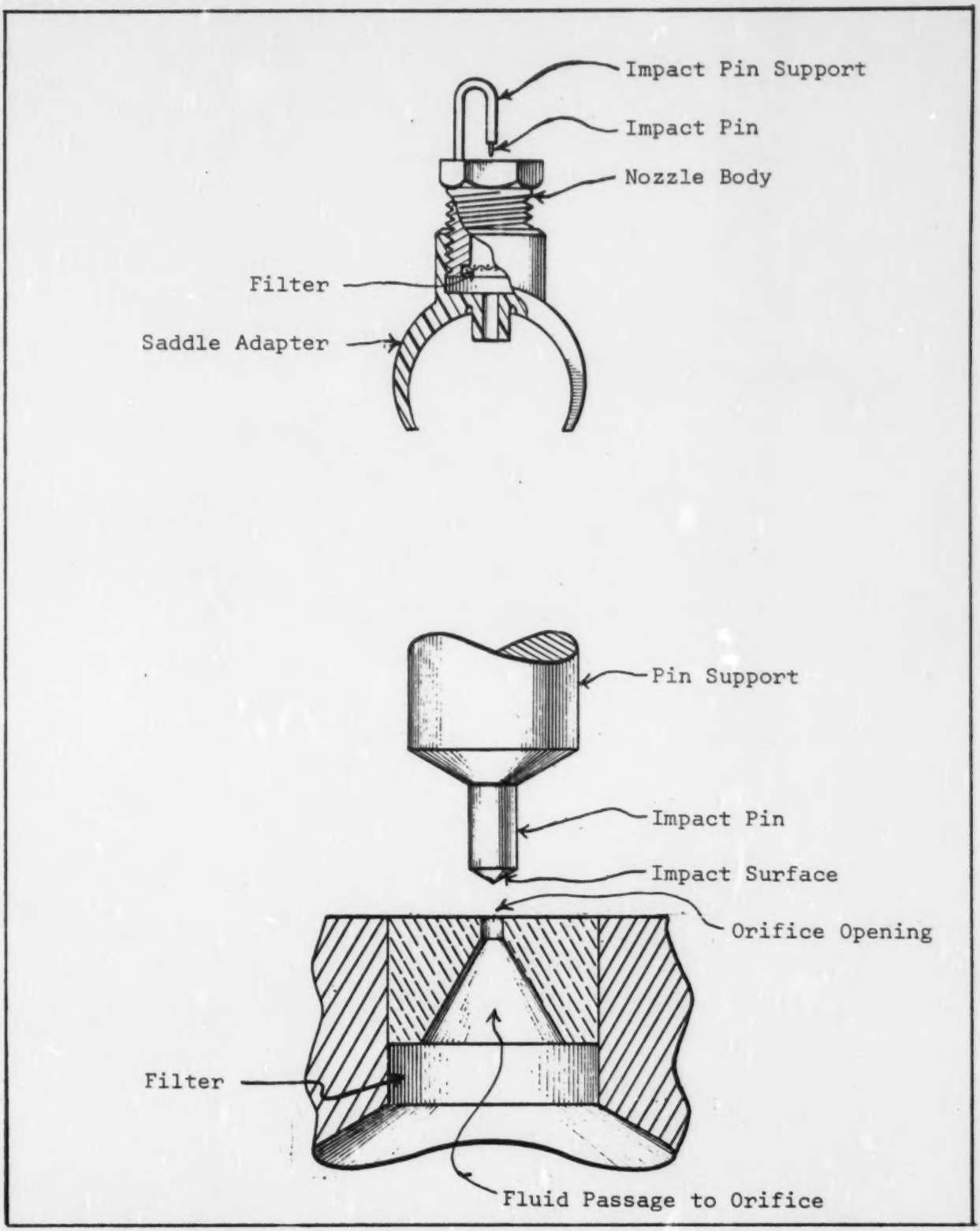


FIG. 12 SCHEMATIC REPRESENTATION OF AN IMPACTION TYPE NOZZLE

6. Theory of Atomization with Direct Pressure Nozzles

It can be argued that the forces involved in the atomization of fluids with direct pressure nozzles are the surface tension of the fluid and an acceleration force experienced by the expanding disk or cone of fluid after it leaves the orifice.

With an impaction type nozzle the fluid exits from the orifice as a cylindrical jet and then spreads into an expanding hollow cone after striking the impact pin. As the cone of fluid expands from the orifice opening the sheet of fluid becomes thinner and tends to break into turbulent ripples which then separate into streamers that are still attached to the main mass of the expanding cone of fluid. At a given distance from the center of the orifice the thickness of the expanding conical sheet will be directly proportional to the diameter of the jet as it leaves the orifice.

The acceleration forces will be proportional to the changing velocities in the expanding cone of fluid and these velocities in turn are always proportional to the velocity of the jet of fluid as it exits from the orifice. Thus it can be argued that the force of surface tension of the fluid is opposed by a force that is proportional to the mass of a droplet forming at the end of one of the streamers and the acceleration that the mass is undergoing.

The theory for droplet making from spinning devices is well known and well tested. From that theory it is known that for any given spinning device the only properties of the fluid that will affect drop size are surface tension and density of the fluid. If the device is operating under conditions of constant rpm and constant flow rate, then the drop size will be directly proportional to the square root of surface tension and inversely proportional to the square root of the density of the fluid. The other terms in the drop size equation which is discussed in Section 5 of Stage I of this report are terms that relate to the size of the spinning device and the velocity imparted to the fluid. It can be assumed that the same fluid properties will affect droplet size in any atomization device and thus the MMD would always be proportional to $(T/\rho)^{\frac{1}{2}}$.

Our experiments with direct pressure nozzles have shown that for any given fluid the MMD is always directly proportional to the diameter of the fluid jet after it exits the nozzle orifice and inversely proportional to the velocity of the jet. Thus we can write an empirical equation in the following form:

$$(1) \quad MMD = C_1 \, (T/\rho)^{\frac{1}{2}} (D/v)$$

where: MMD = mass median diameter of the drop size spectrum

T = Surface tension of the fluid

ρ = Fluid density

D = Diameter of the fluid jet

v = Velocity of fluid jet as it leaves the orifice

p = Pressure

This equation can also be written in the following form:

$$(2) \quad MMD = C_2 (T/p)^{\frac{1}{2}} D$$

where: p = Pressure drop across the nozzle orifice

Equation (2) follows from equation (1) since the velocity of the jet can be stated from Bernoulli's law as:

$$(3) \quad v = (2p/\rho)^{\frac{1}{2}}$$

For orifice diameters .010" and smaller the diameter of the jet is equal to orifice diameter, for orifice diameters .020" and larger jet diameter equals 0.787 times orifice diameter.

To apply equation (3) as it is written, a consistent system of units must be used, such as:

p	ρ	v
lb/ft^2	$slug/ft^3$	ft/s
N/m^2	kg/m^3	m/s
$dyne/cm^2$	g/cm^3	cm/s

When the constants in equations (1) and (2) are determined experimentally for a given set of conditions, the equations work quite well to predict MMD's when nozzle orifices are varied from about .01" to .075" and fluid properties are varied from those of pure water to those of the solutions used in this project. Equations (1) and (2) were found to predict quite accurately the MMD's produced under static conditions by the various direct pressure nozzles and fluids used during this project. If a consistent set of units is used then the constants C_1 and C_2 have dimensions of $L^{-\frac{1}{2}}$ and $C_1 = 1.414 \times C_2$. The absolute value of the constants obviously depends on the units used.

STAGE III

DESIGN OF AN AIRBORNE PROTOTYPE ATOMIZATION SYSTEM

1. Atomization Device

In theory all of the atomization devices investigated during this project would be capable of producing solution droplets in the desired size ranges. However, for a number of reasons, most of which had to do with the practicality of the system, it was decided that direct pressure impaction type nozzles would be best suited for the task.

Direct pressure nozzles are inherently the simplest of the atomization devices tested and therefore offer the probability of being the most reliable. Compared to air atomization devices the direct pressure nozzles proved to be more than an order of magnitude more efficient in terms of power requirements. In addition, air nozzles proved to be more susceptible to clogging because of the narrow passages that are required for handling the air and liquids. Although air nozzles would require approximately 300 H.P. as compared to less than 30 H.P. for direct pressure nozzles, it was realized that this might not be significant if substantial quantities of bleed air were available from an aircraft turbine engine. However, since it was desirable to operate the prototype system from piston type aircraft, the possibility of using bleed air was not looked into.

Spinning type atomization devices did prove to be very efficient in terms of power required but are very complex devices because of the high rpm's (approximately 70 000 rpm) that would be required to produce droplets in the smaller ranges. In addition, because of the low output of spinning devices when small droplets are being produced, such a large number of devices would be required that the system would be impractical for use from an airplane. It was determined that approximately 120 spinning cylinders, each operating at 70 000 rpm, would be required to produce 2 liters per second of droplets in the smallest size category.

Direct pressure impaction type nozzles offer the best compromises and therefore were chosen to be used in the prototype system design. The operating characteristics for direct pressure nozzles when atomizing ammonium nitrate-urea solutions are shown in Fig. 10. From the data presented, 3 nozzles were

chosen that would best span the range of desired MMD's. The nozzle chosen for producing droplets in the smallest size category has a .018mm (.007") orifice diameter. The nozzle that best spans the mid range has a .066mm (.026") orifice diameter and that for the largest particles a 1.4mm (.055") orifice diameter. Flow rates as a function of pressure for the 3 nozzles selected were determined and are shown in Fig. 13. The MMD's that these nozzles are capable of producing are shown in Fig. 14. From Fig. 14 it can be seen that by using the 3 nozzles selected almost the entire range of desired MMD's can be produced from a small size of 18μm to large sizes of 250μm. The total system output will obviously depend on the number of nozzles used and the capacity of the pump. High pressure pumps are discussed in the next section.

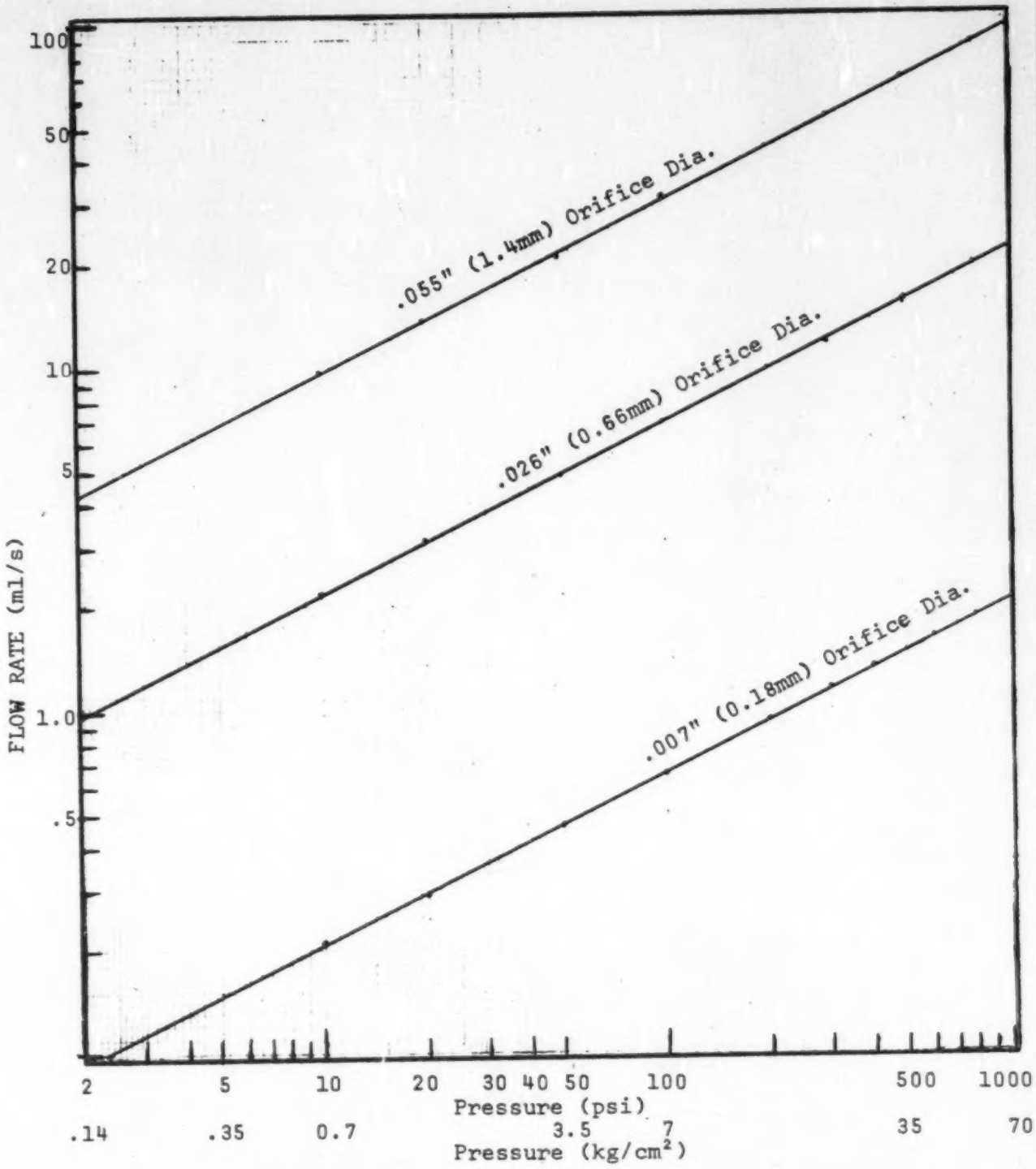


FIG. 13 FLOW RATE FOR 1.32 g/cm³ AMMONIUM NITRATE-UREA SOLUTION THROUGH SELECTED DIRECT PRESSURE IMPACTION TYPE NOZZLES

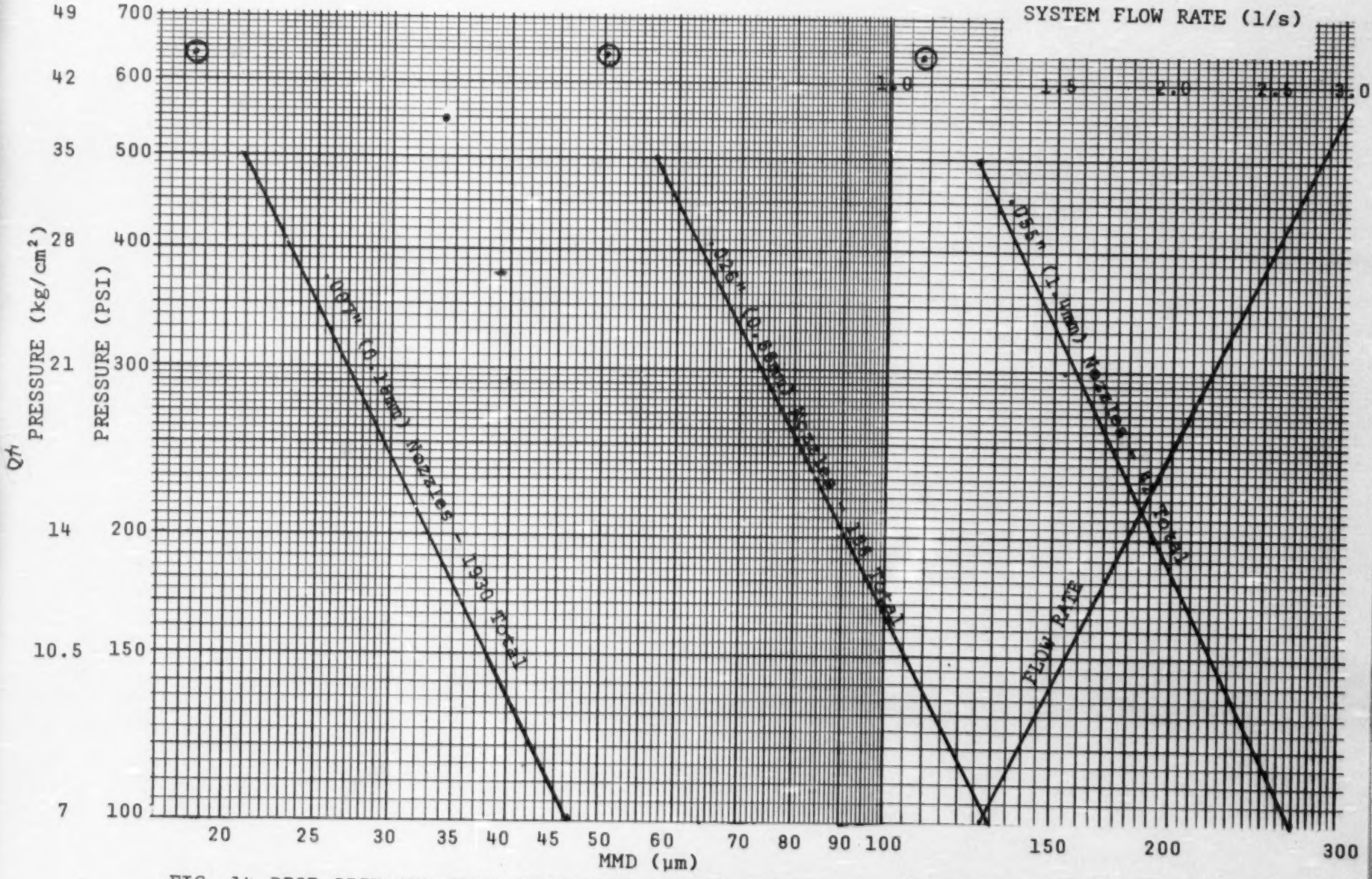


FIG. 14 DROP SIZE AND FLOW RATES PRODUCED BY ATOMIZATION SYSTEM WITH IMPACTION TYPE NOZZLES (110 m/s AIR STREAM; 1.32 g/cm³ AMMONIUM NITRATE-UREA SOLUTION)

2. High Pressure Pumps

To help in selecting a pump from the many available, a number of desirable characteristics were determined. These are:

1. The pump must have an output capacity of at least 2 l/s and a pressure capability of 40 kg/cm^2.

2. All internal wettable surfaces of the pump must be chemically compatible (non corrosive) to the ammonium nitrate-urea solution.

3. The pump should be reasonably efficient in terms of power requirements.

4. It should be clean operating, meaning that it should not produce particulate matter from internal friction of moving parts.

5. The pump must operate reliably under the conditions imposed.

6. Weight is a consideration because the system is to be flown.

7. Availability, especially of parts that might be required for maintenance.

8. Cost.

A number of pumps from several pump manufacturers were investigated. Among the pump makes looked into were Peerless, Kobe, Byron Jackson, Goulds, Delavan, Robbins & Myers, CAT Pumps, Crane Deming, Ingersoll Rand, HyPro, and others. Centrifugal type pumps were chosen as the best compromise of those available. Although centrifugal pumps are generally not as efficient as positive displacement pumps (50% and better efficiency for centrifugal pumps vs. 80% and better for positive displacement), they have other qualities that make them desirable. Piston type positive displacement pumps have many moving parts and generally require routine maintenance not necessary in other types of pumps. Because of their complexity it was felt that piston pumps would be more likely to have minor breakdowns, would be harder to corrosion-proof, and are more susceptible to producing particulate matter in the fluid being pumped.

Centrifugal pumps offer the advantage of being self-limiting in the amount of pressure they can produce. At zero flow, a centrifugal pump will typically produce a maximum pressure

that is only slightly greater than the working pressure of the pump. Positive displacement pumps, on the other hand, can produce very high pressures if the flow is shut off. These pressures are limited only by the power of the pump driver and the bursting strength of the materials used in the system.

Some specialty chemical pumps were investigated and found to have very good non-corrosive properties and in some cases to be capable of producing extremely high pressures. However, the cost of these specialty pumps can easily be ten times that of standard commercial type pumps.

The pump type chosen as most suitable for this project is the standard multi-stage centrifugal type that is available from several manufacturers. Several of these pumps are available with all wetted parts being constructed of either stainless steel or plastic and are therefore chemically suited for pumping the ammonium nitrate-urea solution.

The particular pump chosen for the prototype design is a 45 stage centrifugal pump capable of producing outputs of approximately 3 liters/second at 35 kg/cm^2 with a peak efficiency of 60%. The power required by this pump is a maximum of 25 H.P. Performance curves for the pump are shown in Fig. 15 and specifications in Fig. 16.

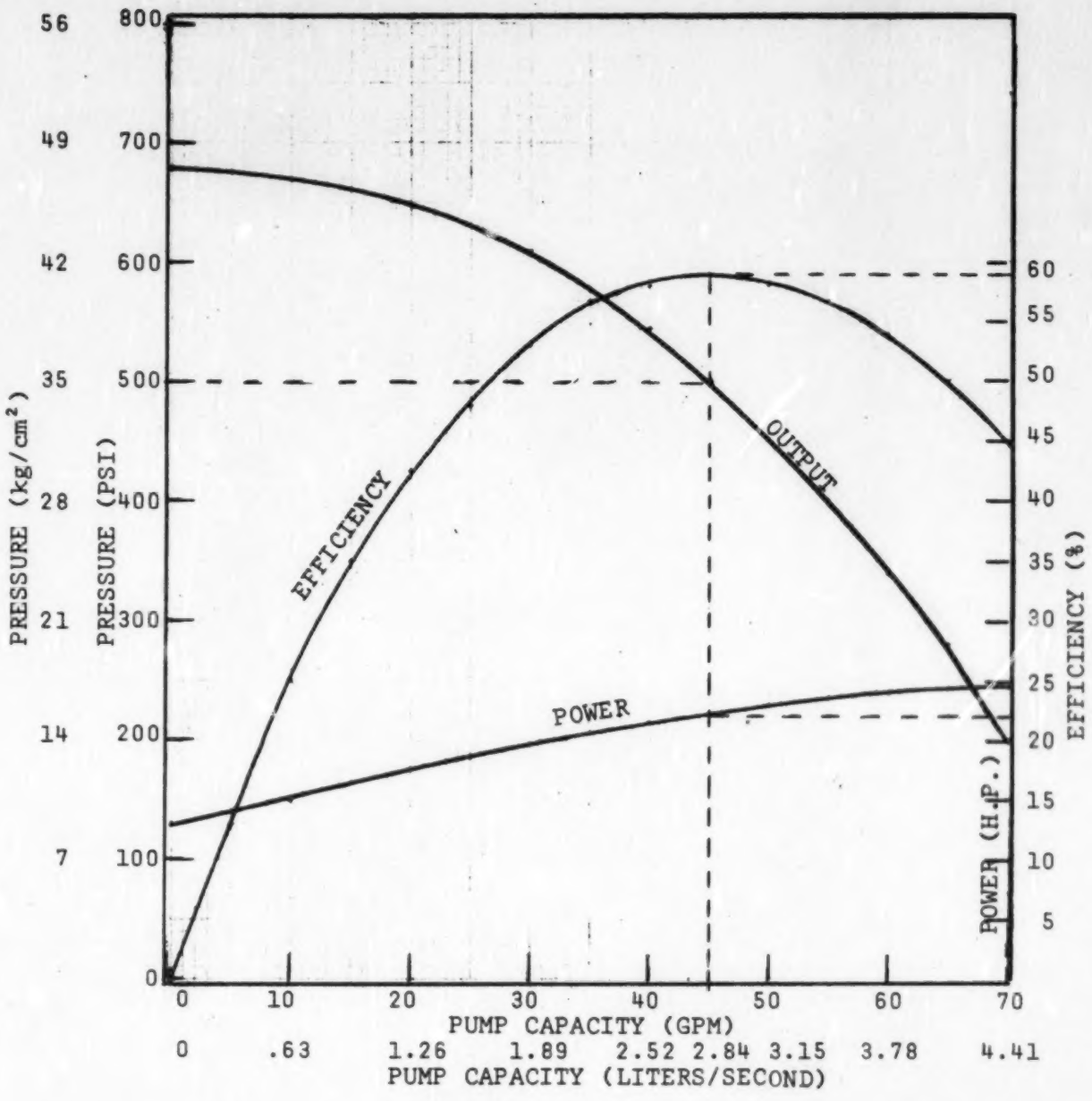
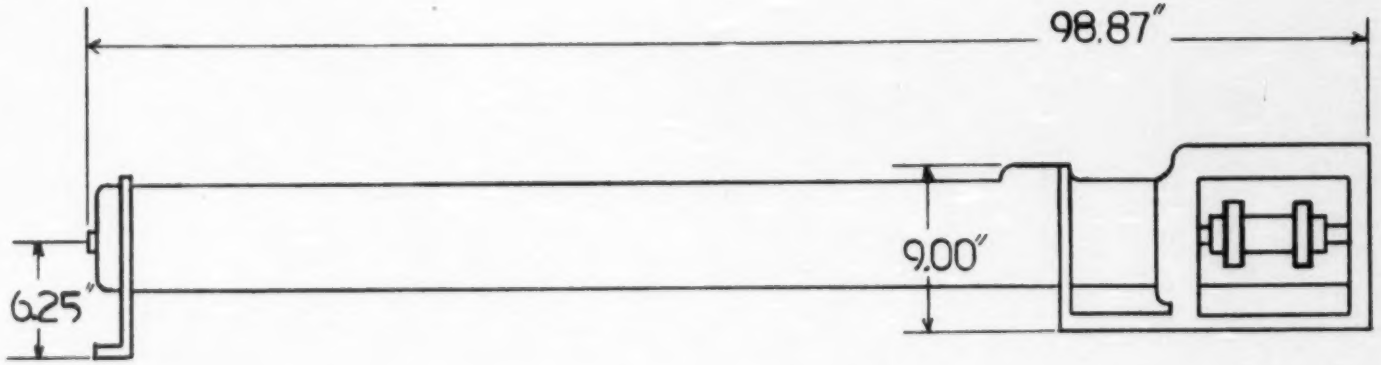


FIG. 15 PERFORMANCE CURVES FOR A 45 STAGE CENTRIFUGAL PUMP OPERATING AT 3500 RPM



Horsepower:	25 HP
Weight:	245 lbs.
Stages:	45
Length:	8.25 ft.
Capacities:	10-60 GPM
Working PSI Max.:	800
Suction PSI Max.:	300
Working Temp. Max.:	160°F
Suction PSI Min.:	Minus 15 H_G or Minus 7.3 PSIG

FIG. 16 SPECIFICATIONS FOR A 3 LITER PER SECOND, 45 STAGE CENTRIFUGAL PUMP OF STAINLESS STEEL CONSTRUCTION AND CAPABLE OF PRODUCING 35 KG/CM^2 PRESSURE AT A PEAK EFFICIENCY OF 60%

3. Pump Driver

The 3 types of drivers considered are electric motors, gasoline engines and diesel engines. Electric motors offer the advantage of simplicity and low maintenance but would require approximately 25 kilowatts of 3-phase 220/440 volt power. Since such power is not readily available on aircraft, and generating plants would add unnecessary weight, electric motors were not considered as a usable pump driver for the system.

Diesel engines are reliable but are generally much heavier than gasoline engines. A gasoline engine was chosen for use in this design as the pump driver offering the best compromises.

The maximum horsepower required by the pump is 25 H.P. However, for a number of reasons the gasoline engine must be capable of producing significantly more horsepower than this. Gasoline engines are typically power rated at their maximum rpm, but for continuous use must be run at lower rpm and therefore lower horsepower. Gasoline engines are also susceptible to power losses at altitude. Taking these various factors into account, a 4 cylinder, 2.9 liter displacement, air-cooled gasoline engine rated at 65 maximum H.P. was chosen. The operating characteristics and specifications for this engine are shown in Figs. 17 and 18.

From Fig. 17 it can be seen that at 10 000 ft. altitude the engine will produce only about 60% of its sea level power at a given rpm. At 1900 rpm the engine will produce 50 H.P. at sea level and approximately 30 H.P. at 10 000 ft. Since the pump will require a maximum of 25 H.P., the 30 H.P. available from the engine would still allow an extra 5 H.P. for function losses in the clutch and drive mechanism of the engine.

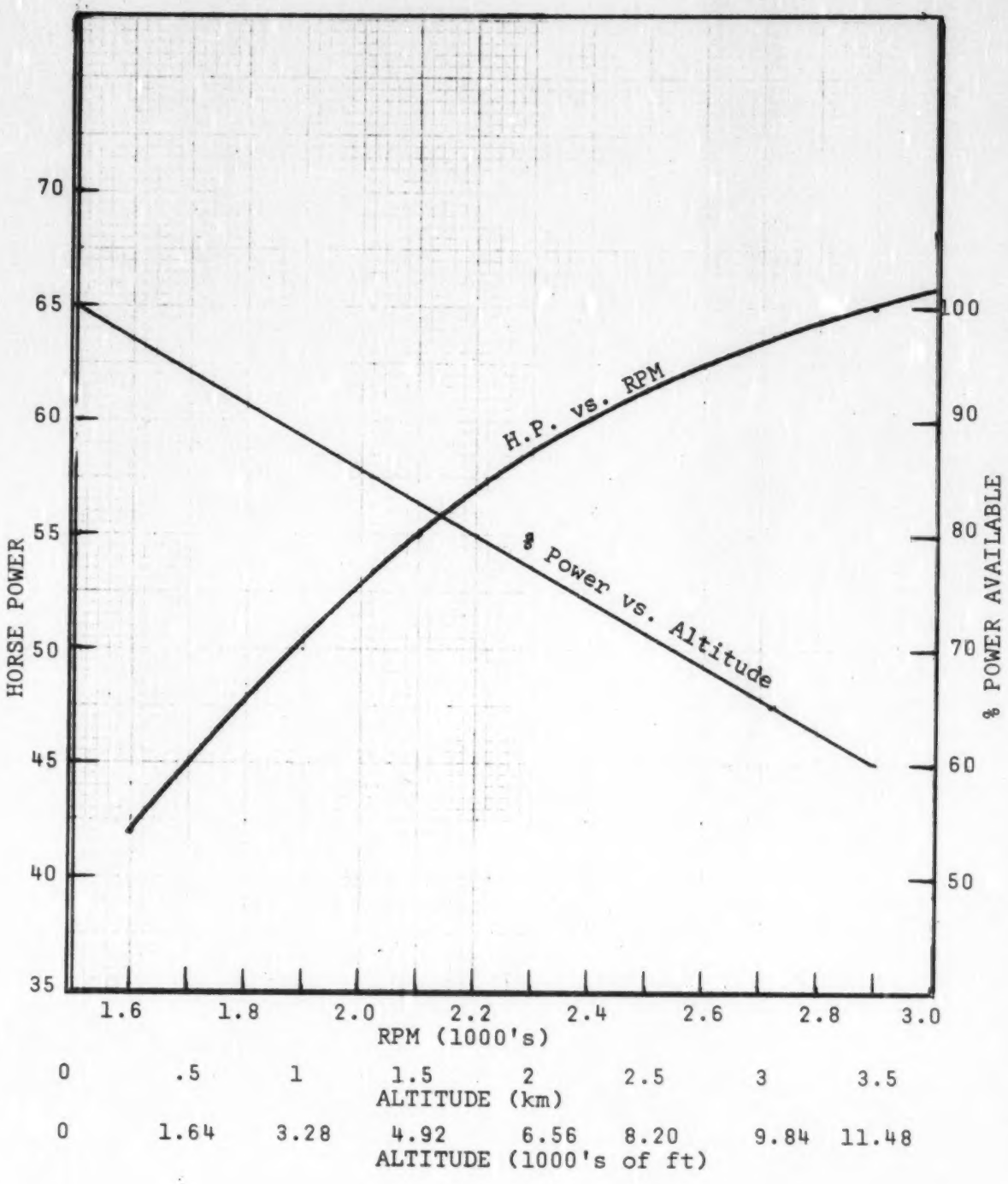
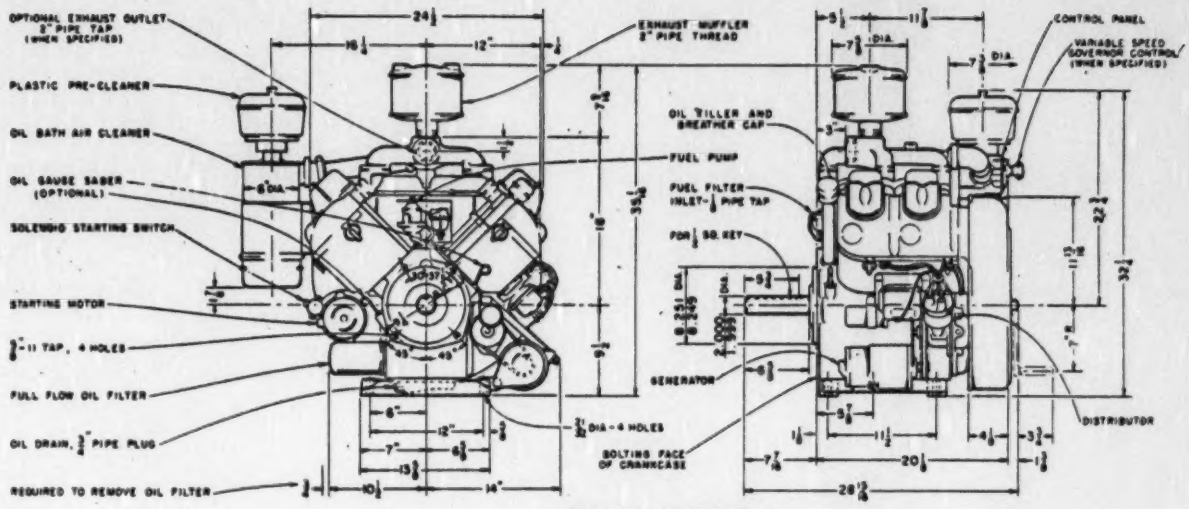


FIG. 17 EFFECTS OF RPM AND ALTITUDE ON POWER OUTPUT OF A 65 H.P. GASOLINE ENGINE

INSTALLATION DIMENSIONS



Open Unit with Stub Shaft

ENGINEERING SPECIFICATIONS:

Number of Cylinders	4
Spark Plug — Size	14mm — Long Reach
Pistons	Aluminum
Piston Pins — Full Floating Type	15/16" Dia.
Valves — Exhaust	Heat Resisting Alloy Steel, 1 5/16" Dia.
Inlet	Silcrome — XB 1 5/16" Dia.
Valve Seat Inserts — Inlet & Exhaust	Ni-Resist
Valve Rotators, Exhaust Only	Positive Type
Replaceable Valve Stem Guides	Cast Iron
Valve Location	Valve in Head
Cylinders — Individual Barrels	Nickel Iron
Honed to Insure Precision Bore	
Cylinder Heads — Individually cast	Aluminum
Crankshaft	Dynamically Balanced, Heat Treated Drop Forging
Camshaft	Alloy Cast Iron, 3 Bearing Journals
Crankcase	Cast Iron
Main Bearing — End	Tapered Roller
Center	Straight Roller — Split Outer Race — Hardened Crankshaft Journal
Connecting Rods	Steel Forging, 7" Long
Connecting Rod Bearings, Replaceable Shells	2 1/8" Dia. x 1 3/16" Long, Overplated, Copper Lead On Steel
Rocker Arms	Malleable Iron With Hardened Noses
Tappet Adjusting Screw	Hardened Steel With Self-Locking Threads
Exhaust Outlet	2" Pipe Thread
Oil Required in Crankcase	6 Qts.
Weights	
Standard Engine with Stub Shaft	530 Lbs.
Standard Engine Crated	625 Lbs.
Clutch Assembly Add	120 Lbs.
Clutch Reduction Assembly Add	220 Lbs.

STANDARD EQUIPMENT:

ROTATION: Counter-clockwise facing power take-off shaft.

LUBRICATION: Gear pump supplies positive full-pressure lubrication to connecting-rod bearings, camshaft bearings, tappet walls, and rocker-arm bearings. Governor and gear train are lubricated by a pressurized jet spray. The crankshaft main bearings, cylinder walls, and piston pins are lubricated by an oil mist.

OIL PRESSURE GAUGE: Checks lubricating pressures.

IGNITION: 12-volt distributor ignition.

CARBURETOR: 1-inch standard float-feed type, designed for easy starting and economical performance . . . anti-dieseling solenoid valve assures immediate stop.

AIR CLEANER: Oil-bath air cleaner coupled with a plastic collector-type pre-cleaner for efficient air filtration.

GOVERNOR: Built-in centrifugal flyball type.

FUEL PUMP: Has mechanically operated pump and glass-bowl fuel strainer.

OIL FILTER: Wisconsin full-flow oil filter for 100% filtration.

ELECTRIC STARTER AND GENERATOR: 12-volt starter equipped with solenoid switch and 17-amp. belt-driven closed-frame generator with 3-step regulator.

CONTROL PANEL: Conveniently located on top of air shroud at front end of engine. Consists of choke and variable-speed governor controls, ignition-starter switch, ammeter, and oil pressure gauge.

HIGH-TEMPERATURE SAFETY SWITCH: Provides automatic safeguard against lack of proper engine care.

FIG. 18 SPECIFICATIONS FOR A 2.9 LITER, 4 CYCLE, 4 CYLINDER AIR COOLED GASOLINE ENGINE

4. Atomization System

The system design shown schematically in Fig. 19 uses the performance characteristics of the pump, the engine, and the nozzles discussed in previous sections. Using these components the limiting factor for flow rate is the pump output. For design purposes it was decided to operate the pump at its peak efficiency point of 2.84 l/s and 35 kg/cm^2 output. The number of nozzles required to make use of this output can be determined from Fig. 13.

From Fig. 13 it can be seen that 1930 nozzles with an orifice diameter of 0.18mm will give a flow of 2.84 l/s at 35 kg/cm^2 pressure. Approximately 186 0.66mm orifice diameter nozzles and 42 1.4mm orifice diameter nozzles will be required to give the same flow of 2.84 l/s. Using the operating characteristics of these nozzles, the system flow rate as a function of pressure was calculated and is presented as the right hand curve in Fig. 14.

It can be seen from Fig. 14 that by adjusting the pressure output of the pump from between 7 kg/cm^2 and 35 kg/cm^2 the system flow rates will vary from 1.3 l/s to 2.84 l/s. MMD's produced will depend on which set of nozzles is being used and the operating pressure. Additional flow control can be obtained by turning off portions of the nozzles and shunting the excess flow from the pump through a pressure regulator.

In the design shown in Fig. 19 the smallest nozzles can be operated in steps of 1/4, 1/2, 3/4 and all nozzles on. The two larger size nozzle systems can be operated either 1/2 or full on. An additional set of operating conditions is shown by the circled dots near the top of the graph in Fig. 14. These 3 dots represent the maximum pressures and smallest MMD's obtainable when only half of the nozzles in any given set are in operation and the pump pressure regulator is adjusted to give maximum obtainable pressure from the pump at these flow rates.

Under these conditions MMD's of 18μm, 50μm, and 110μm are obtainable. The materials used in the design shown schematically in Fig. 19 are aluminum for the plumbing, stainless steel for the fittings, aluminum for the storage tank, and both stainless steel and plastic in the pump, filters, valves and meters. All materials are available as standard, off-the-shelf items.

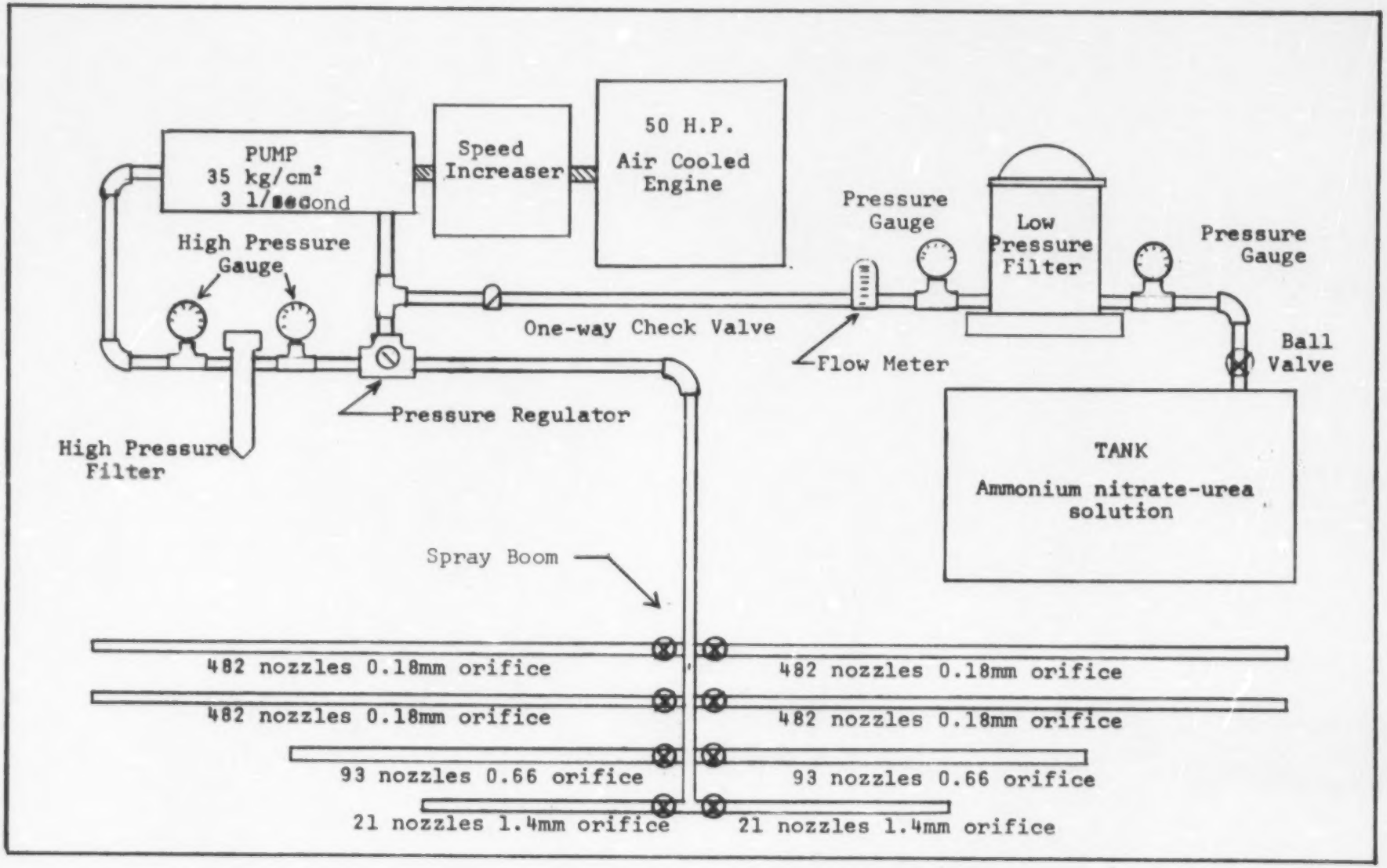


FIG. 19 SCHEMATIC REPRESENTATION OF AIRBORNE ATOMIZATION SYSTEM. MMD'S CONTROLLABLE FROM 20μm TO 250μm. FLOW CONTROLLABLE FROM 0.5 TO 3 LITER/SECOND

The storage tank size has not been specified since its final selection will depend both on the requirements of the seeding experiment and on the space available and weight carrying capability of the aircraft finally selected. If the aircraft has a payload capability of approximately 7000 lbs. (3200 kg) then about 4000 lbs. (1800 kg) will be available for seeding material. With this payload if the system is operated at its maximum output of 2.84 liters per second, approximately 8 minutes of seeding time would be available.

The spray boom and system plumbing depicted in Fig. 19 is shown in schematic form only. A detailed design cannot be finalized until a specific aircraft is chosen. For example, even among DC-3's the physical layout of the aircraft will vary significantly depending upon which model is chosen and upon how much modernizing has been done to that model. In finalizing the plumbing design three main considerations must be taken into account. One is that pressure drops between the output of the pump and the end of the spray boom be kept reasonable. A pressure drop of 50 psi is probably acceptable. A second consideration is that the spray boom be located so as to minimize or prevent wetting of any surface of the aircraft. The third consideration is that the entire installation be mounted so as to conform to standard flight safety procedures and applicable FAA regulations.

One inch diameter pipe is probably adequate for the entire installation although smaller piping might be used for the spray booms. At a flow rate of 45 gallons per minute, 1" pipe has a pressure drop of approximately 50 lbs. per 100 ft depending on the type of pipe used. Since the feedline plumbing will most likely be considerably shorter than 100 ft, 1" pipe should be satisfactory.

In the spray boom the minimum recommended spacing for the 0.18mm orifice nozzles is 1", for the 0.66mm orifice nozzles 2", and for the 1.4mm orifice nozzles 3". Thus for the small nozzles if two branches of the boom are used per wing, the booms would have to be 40 ft in length. If three branches are used, the booms would have to be 27 ft. Maximum flow rate if only two branches are used would be 11.25 gpm per branch. If three branches are used, maximum flow rate would be 7.5 gpm per branch. One-half inch diameter pipe has a pressure drop of approximately 25 psi in 40 ft at a flow of 11 gpm so either 1/2" or 1" pipe could be used for the boom. The same applies for the other two booms since they can be considerably shorter than the booms for the small nozzles. For example, one branch of the boom for the 0.66mm nozzles need only be 16 ft long, and for the 1.4mm nozzles only 6 ft long.

5. Solution Preparation Procedures

One of the criterion set out at the beginning of the project was that a solution containing approximately 44% (by weight) of ammonium nitrate, 36% urea and 20% water would be suitable. Solutions mixed in this ratio proved to have a density of 1.32 g/cm^3. All atomization tests were conducted with such a mixture.

It was determined that commercial grade fertilizers are quite adequate and much cheaper than more purified chemicals but that the solutions obtained from the fertilizers would require prefiltering so as not to unduly load up the filters in the atomization system. Since the chemicals used produce an endothermic chemical reaction when put into solution in water, it is necessary to let the solution stand for some time and warm up before the entire amount of solids will go into solution. Since the solution also requires filtering, it would be necessary to make the mixture several days in advance of its anticipated use.

Some concern was given as to whether the 1.32 g solution would have any tendency to crystalize and salt out in the plumbing system and nozzles during operation. Since it is anticipated that the seeding aircraft could operate at temperatures as cold as 0°C, tests were conducted to find out whether the solution would begin to precipitate at these temperatures. During the tests it was found that no precipitation was evident until the solution was cooled to approximately -5°C. When the solution was warmed back above 0°C all precipitated crystals went back into solution. Thus it was determined that crystalization would not be a problem under normal operating conditions.

6. Bill of Materials

1. Pump - 2 liter per second, 35 kg/cm^2, must be non-corrosive to ammonium nitrate-urea solution.
   Material: stainless steel, aluminum or plastic acceptable (but not brass or bronze).
   Manufacturer: Kobe, Inc. RD-50, Robbins & Myers, Inc., 6P-10, Goulds MB45-500 or equivalent.

2. Pump Driver - Recommend gasoline or diesel engine capable of delivering 25 HP to the pump at 10 000 ft altitude.
   Manufacturer: Waukesha Model VRN232U, Wisconsin Model V-465D or equivalent.

3. Clutch and Speed Increaser (usually part of engine package).
   Manufacturer: Amarillo Model 150 or equivalent.

4. Plumbing and Fittings - 1/2" or 1"
   Stainless Steel: Ladish Mfg. Co.
   Aluminum: Alcoa
   PVC Schedule 80: Lasco, Robbins & Myers, or equivalent.

5. Pressure Gauges -
   0-100 psi: Marshalltown Mfg. Co. #83519 or equiv.
   0-1000 psi: Ametek/U.S. Gauge #47496 or equiv.

6. Low Pressure Filter -
   Harmsco Waterbetter WB-6, 50 gpm, or equivalent.

7. Flow Meter - 50 gpm
   Manufacturer: Rotameter Mod. 9-HCFb, 93-J or equiv.
   Brooks Series 3604-12, all stainless, or equiv.

8. Ball Valve - 1"
   Manufacturer: Apollo Mod. 76-105 316, stainless, Worcester 411T, stainless, or equiv.

9. Solution Tank - not specified. Will depend on aircraft load carrying capabilities and seeding capability desired by the Bureau of Reclamation.

10. Check Valve - Cooper No. 2001 or equivalent.

11. Pressure Regulator - aluminum or stainless steel.
    Spraying Systems Co., Type 6815G AL-3/4-HSS-700 or equiv.

12. High Pressure Filter - Filterite 24FMS4A-2 or equiv.

13. Atomizing Nozzles - Direct pressure, must be certified to produce 20µm MMD to 200µm MMD spray of ammonium nitrate-urea solution. Mee DPI series, ss, or equiv.

7. Costs

The costs given below are for estimating purposes only and are not in any way to be considered as a quote. The estimates were prepared using costing procedures that are standard in industry and are thought to fairly represent an estimate of what a prototype system might cost.

Actual costs in a bid situation will depend on the skill, ingenuity and costing practices of the firm or institute making the bid. As discussed in the preceding sections there are a wide variety of components that would be suitable for use in a final system. All design details have been worked out and specified, except that final dimensions and specific components are not listed.

Final dimensions will depend on the specific aircraft to be used (not just the type of aircraft such as a DC-3 because details of a specific aircraft might, and usually do, vary considerably within a given class). Specific components chosen will depend upon the commercial practices, skill and ingenuity of the group doing the final design.

The estimated costs for producing an airborne prototype system are summarized below:

1.	Pump, engine and auxiliary equipment	$ 16,250
2.	High pressure and low pressure manifolds consisting of filters, pressure gauges, flow gauges and pressure regulator	2,500
3.	Control panel	2,500
4.	Solution feed tank	2,500
5.	Atomization system consisting of 2158 direct pressure impaction type nozzles plus control valves and distribution system	28,500
6.	Engineering and testing	10,000
	Total estimated cost (does not include installation)	$ 62,250